ESD-TR-65-462

(FINAL REPORT)

HUMAN FACTORS RESEARCH IN 3-D DATA PRESENTATION

JUNE 1965

DECISION SCIENCES LABORATORY
DEPUTY FOR ENGINEERING & TECHNOLOGY
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

ESRH

(Prepared under Contract No. AF 19(628)-274 by ITT Federal Laboratories, 500 Washington Avenue Nutley, New Jersey 07110)

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HUMAN FACTORS RESEARCH IN 3-D DATA PRESENTATION

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June 1965

FOREWORD

This research was accomplished under Project 7682, Task 768201, Contract AF19(628)-274 by ITT Federal Laboratories, Nutley, New Jersey. Contract Monitor was Dr. D. W. Connolly, Decision Sciences Laboratory. The studies reported were performed during the period from September 1962 through May 1965.

This Technical Report has been reviewed and is approved.

Donald W. Connolly

DONALD W. CONNOLLY
Project Officer
Decision Sciences Laboratory

for James S. Duva

ROY MORGAN, Colonel, USAF
Director
Decision Sciences Laboratory

ABSTRACT

A series of experiments was performed to evaluate some of the operating characteristics and potential utility of a volumetric (i.e., real) three-dimensional display produced by projection of a CRT image onto a rotating translucent screen. Some of the variables tested were perceptibility of relative location of point targets in close proximity, perception of location of point targets relative to display boundaries and perception of absolute and relative motion of targets in the volume. Estimation of location and motion were found to be highly accurate and quite rapid. While the results do not point conclusively to specific applications, the utility of volumetric 3-D in making fine position and motion discriminations has been demonstrated. Further study would be required to ascertain utility in practical situations such as air traffic control, space surveillance, etc.

C O N T E N T S

F I G U R E S

FIGURES
(continued)

TABLES

FINAL REPORT

Contract No. AF19(628)-274

HUMAN-FACTORS RESEARCH IN 3-D DATA PRESENTATION

1.0 Introduction

Using an ITTFL-designed display, a series of experiments were conducted which provide data indicating the utility of 3-D volumetric display for various practical applications. The display device and salient features of the experimental situation and procedures are described in Section 2.0. The psychophysical experiments evaluating the perceptual characteristics of volumetric display are presented in the following sections (Sections 3.0 - 7.0). The results of each experiment are discussed in these sections and are summarized in the concluding section.

2.0 General Experimental Situation

2.1 Overall Physical Layout

The experimental environment consisted of two rooms. One room held the display device; the other, the experimenter's station. The general configuration of the subject's room and the location of the display are shown in Figure 2-1. A brief description of the output characteristics of the display device is given in section 2.2. The specification and control of ambient illumination in the experimental room is discussed in section 2.3.

2.2 Display Device and Standard Viewing Position

A photograph of the display device is shown as Figure 2-2. The display is obtained by sweeping a display plane through the volume contained by the transparent cover of the display. In particular, a plane translucent screen is rotated about a vertical axis to sweep out a volume of revolution. Light images appearing on the face of a CRT are optically projected onto the screen at the proper rotational position, and repeated at a rate above visual flicker. Since the screen is translucent, the image may be seen by reflection from one side and transmission from the other side. The result is a light image, apparently freely displayed in space, visible from all sides and above. (The signals which generate the sequenced images on the CRT at the proper time are obtained by scanning an electrical storage or buffer.) The screen sweeps out a cylinder 5 inches high and 24 inches in diameter. Targets can be projected within a 10 inch diameter. The speed of rotation was held constant in these experiments at 1000 rpm.

A standard viewing position was adopted and used throughout these experiments (see Figure 2-2). The subject's eyes were approximately two feet from the vertical center of rotation of the display and so positioned that the subject looked downward into the display volume through the top of the display. The line-of-sight to the mid-altitude point on the rotational center was depressed approximately 30° from the horizontal. This viewing position was maintained more or less rigidly, depending on its criticality for the observations being made. In general, the observer's ability to maintain the standard position was considered sufficiently precise and no physical constraint was used. In the study of target motion threshold, the observer viewed the display through an oscilloscope viewing hood mounted in an opaque screen at the standard viewing position. The purpose

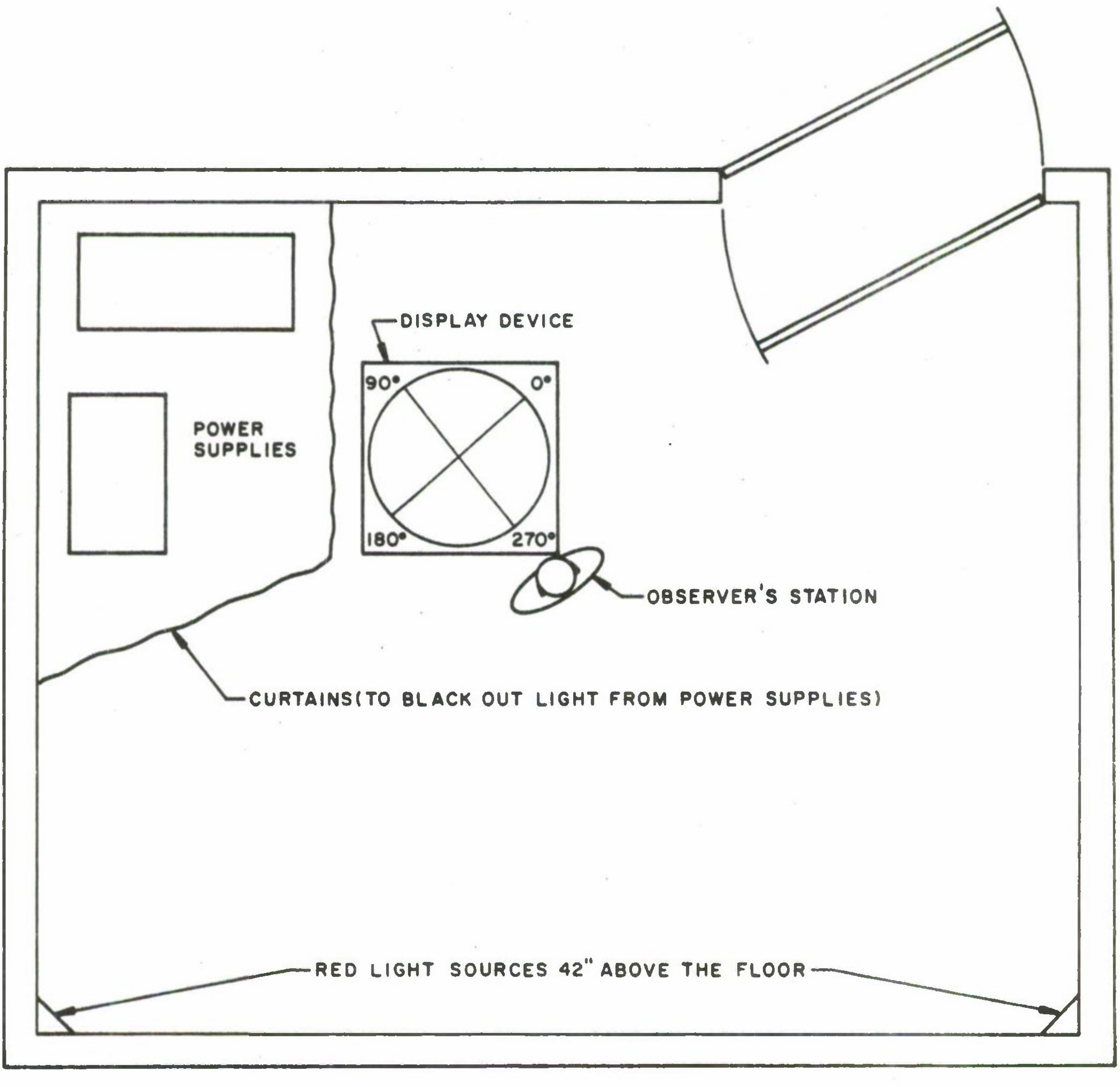

FIGURE 2-1

DIAGRAM OF EXPERIMENTAL ROOM

FIGURE 2-2

DISPLAY DEVICE AND OBSERVER IN STANDARD POSITION of the added constraint in this experiment (IV) was primarily to restrict the field of view and, consequently, the frame of reference available as a basis for judgments of target motion. A more rigorous constraint was introduced in Experiment III. In this case the entire display volume was covered by a box whose inside walls were painted flat black. A slot (2" x 6") for viewing was located on the box so that the observer could remain at the standard viewing position and see the entire display volume. The top of the box was removed and recovered with red translucent plastic and a light box containing a rheostat-controlled 75 watt frosted bulb was placed atop this plastic. The illumination inside the box was varied until a dark-adapted observer could see the physical display volume boundaries but nothing else. Essentially, the result was to limit cues for locating a point target to those provided by the display itself. Thus, all of the experimental results reported herein are based on a fixed viewing position and are not necessarily equivalent to the results which would be obtained by an observer free to shift head position to improve performance in the task at hand. In particular, since we were concerned with analyzing the effect of the angle of regard to the viewing screen on various perceptual tasks, the observer was instructed to maintain the standard position even though a small head movement might produce a significant improvement in the line-of-sight to the screen.

2.3 Ambient Illumination

Illumination of the display room was available from overhead fluorescent lighting which covered the ceiling of the room. This extended source was diffused through a grating and was controllable in intensity. To provide lower ambient levels and avoid reflection of the overhead fixtures from the display cover, incandescent lights were mounted in two corners of the room as shown in Figure 2-1. These lights were diffused through translucent white paper and, when red illumination was desired, were additionally filtered through a sheet of red cellophane. Controlled in intensity by a variac, these lights were the illumination source for most of the experiments reported here.

To equiate the luminous intensity of the red and white illumination, measures were taken from the surface of the diffusing screen with a Spectra Brightness Spot Meter, a photo-electric device having spectral sensitivity approximating that of the human eye. As an additional check, readings were taken at the display with a Macbeth Illuminometer. These readings confirmed the equation of red and white illumination levels established with the Spectra meter.

The primary purpose of the Macbeth Illuminometer readings was to provide a description of the ambient illumination at the display in generalizable terms, i.e., not dependent on the particular light sources used in these experiments. For this purpose, calibration curves for both red and white illumination were obtained with measurements taken from the standard reflecting plate of the Macbeth. The reflecting plate was positioned just above the display with its reflecting surface in the plane of the display screen at 0° azimuth and facing toward the standard viewing position. The measurements taken in this manner provide a basis for effectively reproducing the ambient illumination levels used in these experiments. All experimental findings which are a function of ambient illumination are presented in terms of these measurements. It should be noted, however, that the level thus specified is not a measure of the effective background luminance of the display screen. The specified levels can, of course, be corrected to account for the reflection (or transmission) factor of the display screen, but the effect of screen rotation is still not taken into account. In view of the difficulty of obtaining such measurements, it is best that the measurements presented here be regarded as a general indication of effective luminance levels and as a basis for reproducing the conditions of these experiments.

2.4 Stimulus Calibration and Control

For these experiments, two targets were provided which could be independently controlled in size, position, motion and luminance. After initial calibration, these parameters were controlled primarily by potentiometer settings. When greater accuracy was required (and when a parameter was used as an dependent variable), appropriate voltage measurements were made with an oscilloscope. Any or all of the controls for one of the targets could be operated by the observer and monitored on the experimenter's oscilloscope.

2.4.1 Target Position and Motion

Each target was independently controlled in position (range, altitude, and azimuth) and luminance by a set of four calibrated potentiometers. In addition, independent linear movement of each target could be obtained. Each target could move in any direction in the plane of the display screen. The experimenter could control the distance through which the target moved and, by varying the traversing time for this distance, could control the rate of target motion. Thus, for the rate-matching experiment, the subject controlled the duration of the excursion of one target; this duration was measured on a Berkeley Model 7630 timer and compared with the duration of presentation of the other target which was pre-set by the experimenter.

2.4.2 Target Luminance

Target luminance was calibrated by measuring a target projected onto the stationary screen at several supra-threshold luminance levels. This procedure resulted in a calibration curve which established a linear relationship between target luminance and the setting of a potentiometer which varied the control grid bias of the CRT. Since several system parameters affected the relationship between potentiometer setting and luminance level, the absolute luminance level associated with a given potentiometer setting varied somewhat from session to session. Therefore, a luminance threshold was determined under the conditions of calibration, i.e., in the dark with a stationary screen. Thereafter, to equate luminance among sessions, the luminance level associated with this calibration threshold was assigned to a threshold appropriately determined during each session. Unlike the calibration threshold, the basal threshold for each session was taken with a rotating screen so that the luminance equation among sessions was directly relevant to the conditions of experimental observation.

2.5 Observers

The data reported in these studies was obtained by three experimental psychologists from the staff of ITTFL's Human Factors Group who served as experimenter-observers. These individuals had normal vision and were experienced in psychophysical experimentation.

3.0 Experiment I: Relative Position of "Point" Targets in a Volumetric 3-D Display

Two studies were designed to investigate the perception of two targets in close proximity. The first, presented in this section, studied an operator's ability to superimpose a movable point target on a stationary target separated from it in one display dimension. The second, presented in Section 4, studied the resolution of the display in terms of a specifically defined two-point limen.

3.1 Procedure

The subjects were presented with two point targets whose location could be controlled separately in range (radius) and altitude. The targets, generated in the circumferential mode, were 0.06 inches in diameter with an arc length of 0.5° in azimuth. The first, called the standard target (St) was under the control of the experimenter from outside the testing room. The second, called the comparison target (Co), was under the subject's direct control. The experimenter monitored the position of both targets on an oscilloscope. The subject's task was to superimpose Co on St in accordance with the procedure described in the next paragraph.

St was presented in a random sequence in one of 36 selected positions. The subject was instructed to work in only one dimension at a time, either radius or altitude. Co was entirely under subject control; therefore, at the start of each trial he positioned it at some relatively large, easily perceptible distance from St in the stated dimension. He then moved Co towards St until he was satisfied that they were superimposed. The experimenter recorded the distance (in volts) between the two targets, and instructed the subject to move the Co away from the St in the same dimension as before, but in the opposite direction. This process was repeated for 10 trials in one dimension. The experimenter then superimposed the two targets in that dimension and instructed the subject to move the Co away from the standard in the other dimension. The procedure was repeated for 10 trials in the second dimension. In this way, an estimate of S's superposition error in range and altitude was obtained which was based on 10 measures on each dimension. Both targets were then moved to another of the 36 positions and the entire sequence was repeated.

The 36 St target positions studied were comprised of nine positions at each of four azimuth positions: 0°, 90°, 180° and 270°*. The nine positions at each azimuth were the combinations of three radial positions and three altitude positions. Radial positions, measured in inches from the center of

*These azimuth positions are defined in Figure 2-1.

rotation, were 0.5, 2.25 and 4.0 inches. Altitude positions, measured in inches from the bottom of the display screen, were 1.0, 2.5 and 4.0 inches.

Superposition in azimuth was not studied, since a slight interaction affected the position of St when Co was superpositioned in the same plane. To avoid providing an extraneous cue to the observer, the two targets were slightly separated in azimuth at all times. This separation, about 1/3 the width of the target in azimuth, was not directly perceptible to the observer, although it had a small effect on his performance which is discussed below.

After examining the results for the 36 positions just described it was apparent that supplementary data was desirable. As expected, performance was somewhat poorer when the screen was oriented along the observer's line-of-sight, i.e., at 90° and 270°.

To better define the change in performance as a function of azimuth angle, supplementary data was obtained at angles bracketing 90° and 270°. Thresholds were determined at additional positions 5°, 15°, and 45° on either side of the 90° and 270° azimuth positions. Thresholds at 90° and 270° were also redetermined since it was possible that the earlier determinations were affected by small variations in viewing position. In order to minimize such variations, a headrest was used to aid the observer in maintaining the standard viewing position throughout these supplementary measurements.

The standard red ambient illumination level (defined in Section 2.3) was used throughout. Target luminance was .25 foot-lamberts.

3.2 Results and Discussion

The results are presented graphically in Figures 3-1, 3-2, and 3-3. The results for the two observers are presented separately. Although the results for the two observers are quite similar in most respects, a difference requiring separate treatment arose in the supplementary data on azimuth position (Figure 3-3). To provide a frame of reference for presentation of the supplementary data, individual presentation is also used for the earlier superpositioning data.

Figure 3-1 shows the pattern of errors resulting from superpositioning in range. The uppermost pair of curves in each of the individual observer plots show mean absolute error (i.e., without regard to sign) at the four azimuth positions. The upper curve of the pair is based on all nine target positions used at each azimuth; the lower curve of the pair is based on the mid-screen (mid-range and mid-altitude) position only. The relative position

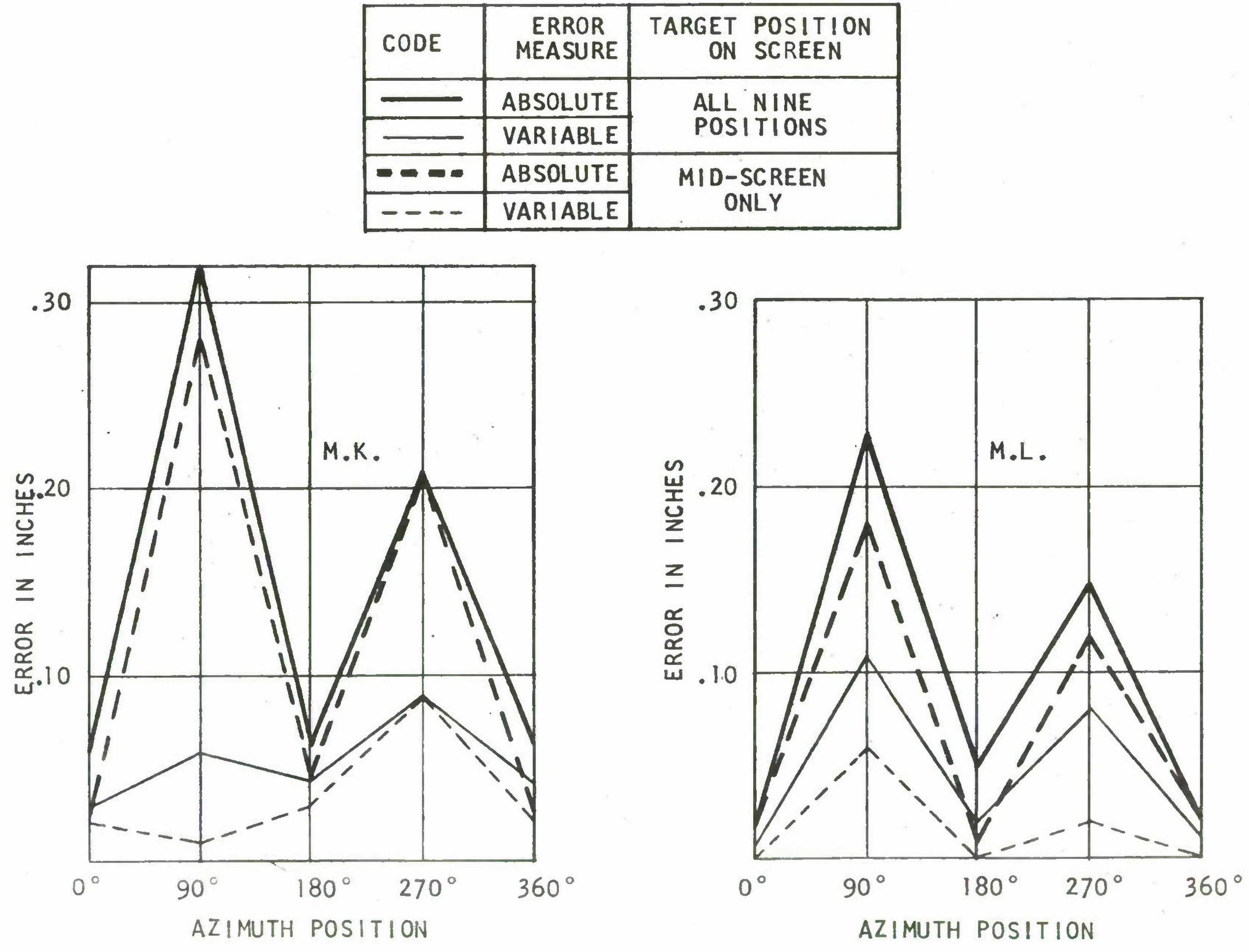

FIGURE 3-1

SUPERPOSITIONING IN RANGE (RADIUS). INDIVIDUAL OBSERVER PLOTS SHOWING MEAN ABSOLUTE ERROR AND MEAN VARIABLE ERROR AS A FUNCTION OF TARGET POSITION IN AZIMUTH of these curves, which holds without exception (and is confirmed by the data for positioning in altitude in Figure 3-2), indicates that performance is better at mid-screen. The variation in absolute error along each of these curves indicates that, as expected, performance is worse at azimuth positions along the observer's line-of-sight. Also, for both observers, absolute error is greater on the side of the display away from the observer (90°) than on the side toward the observer (270°). The pattern of variation in absolute error as a function of azimuth is very similar for the two observers, with Observer M.L. having somewhat smaller errors.

These absolute errors are undesirably large at unfavorable azimuth positions. It is of interest, therefore, to learn more about the composition of these errors. The lower pair of curves in Figure 3-1 is presented for this purpose. These curves show the variable error at each azimuth position. These are derived by subtracting the algebraic means from the absolute means. An algebraic mean error in this type of experiment may be considered an estimate of constant error or direction bias while the absolute mean is an estimate of total error. The difference between the two thus represents variable error. It can be seen that constant error is a major component of the large total error at 90° and 270°. The variation in error magnitude with azimuth, previously noted for absolute error, appears to carry over to variable error, but the pattern is much less pronounced.

Figure 3-2 presents the data for superpositioning in altitude. The general trends and relationships discussed in connection with Figure 3-1 also are evident here with some differences. The combined effect of these differences is a somewhat less pronounced variation of the error measures with azimuth. The values of mean variable error are low and relatively constant, even at the most unfavorable azimuth positions. The degradation in performance at 90° and 270° is still quite marked in the absolute error measure, but the difference in absolute error between those two angles has been lessened. Performance at 90° is little, if any, worse than at 270°. Another quite evident difference is the relatively large constant error component at 180° which is not present in the data for positioning in range.

It is possible, at least at a qualitative level, to account for these differences. The latter one, for example, appears to be related to the slight fixed difference in azimuth position between the standard and variable targets. The variable (Co) target is the closer to the observer at 180° (and is the further of the two at 0°); thus, since the observer is looking down at an angle into the display volume, superpositioning Co along the line-of-sight to St will result in a positive constant error component at 180° and

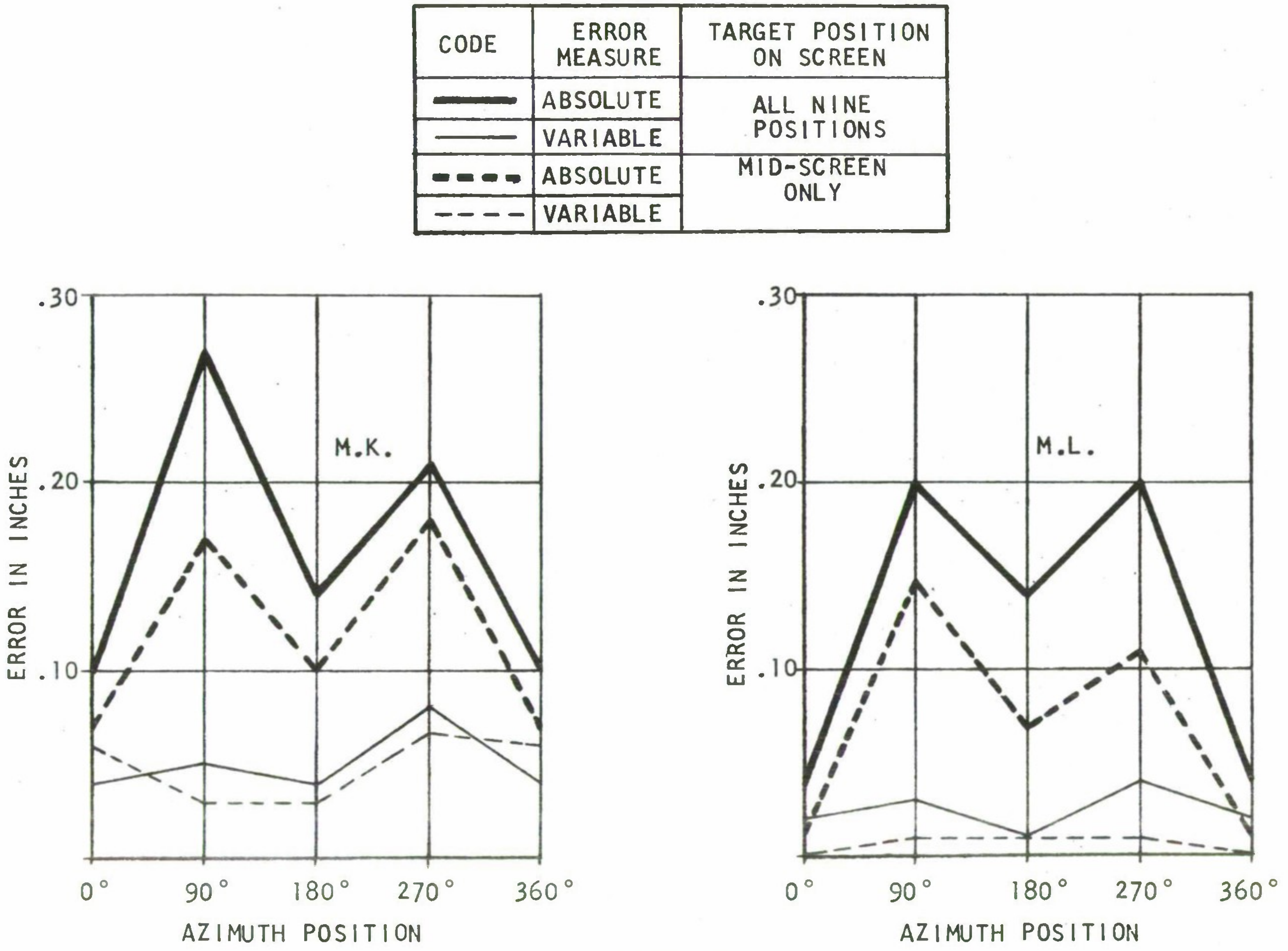

FIGURE 3-2

SUPERPOSITIONING IN ALTITUDE. INDIVIDUAL OBSERVER PLOTS SHOWING MEAN ABSOLUTE ERROR AND MEAN VARIABLE ERROR AS A FUNCTION OF TARGET POSITION IN AZIMUTH a negative constant error component at 0°. However, explanatory factors such as this must be applied consistently and quantitatively to be of real value. Such an analysis is not pursued here because there are variables other than display variables exerting a significant influence on the data. This is particularly evident in the supplementary data.

Figure 3-3 shows the supplementary data gathered to determine the effect of azimuth angle with greater precision. This figure shows mean absolute error as a function of azimuth angle for the mid-screen target position. The results are quite different for the two observers. The data for M.L. are more in accord with expectation, except perhaps for the magnitude of error at 90°. However, higher peaks at 90° and 270°, as evidenced by M.L., are consistent with the notion that there is a relatively narrow azimuth band around each of these angles within which performance is significantly degraded. Using a headrest to control head position, it should be possible to maintain a line-of-sight along the 90°-270° axis with greater precision than in the earlier sessions; consequently, sharper error peaks might be expected. M.L.'s peak errors at 90° and 270° are higher for both range and altitude positioning than the corresponding values from the previous determinations without a headrest. However, this is not the case for M.K.

Figure 3-3 shows that M.K.'s error functions are devoid of sharp peaks. Also, comparing this supplementary data with the corresponding data of Figures 3-1 and 3-2, a large reduction in error is noted. Since these changes do not appear to be attributable to the addition of a headrest, another explanation must be sought. It is little more than a statement of fact to say that M.K. has reduced his constant error greatly; statements regarding the way in which this result was achieved are speculative. One plausible speculation is that M.K. has learned to bisect the interval of uncertainty. Although the direction of initial separation of the standard and variable targets was counterbalanced, the observer was free to reverse direction of adjustment. If the observer always made his final adjustment for a positive direction and stopped just within the interval of uncertainty, a positive constant error would result. If the interval of uncertainty were large, the constant error would be large. Assuming that M.K.'s early superposition data are based on this mode of adjustment, a substantial reduction in constant error might result from a change to a bisection criterion. If the observer operates his control to bracket the interval of uncertainty and then splits the difference, this procedure will tend to eliminate any constant bias

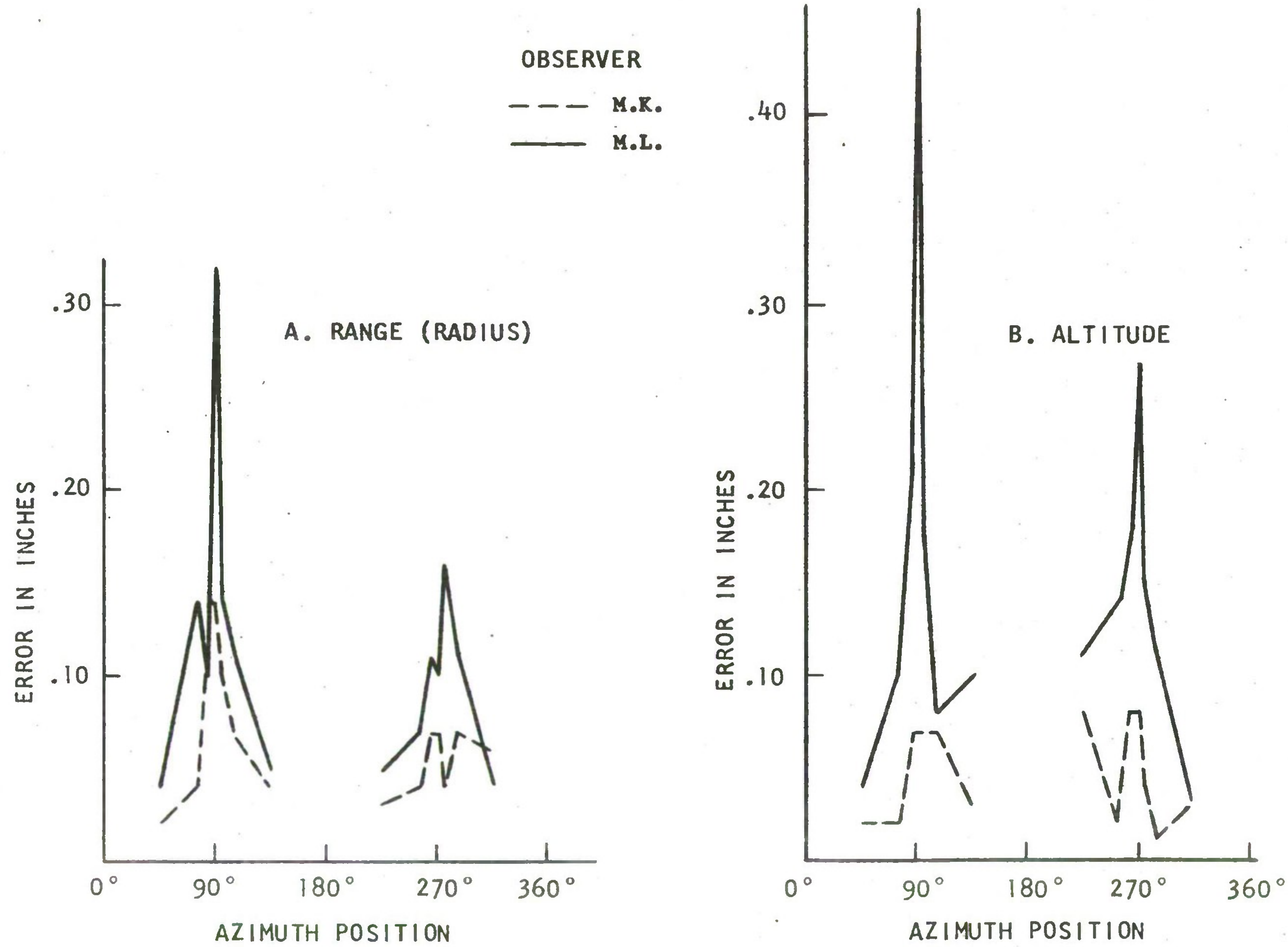

FIGURE 3-3. SUPPLEMENTARY SUPERPOSITIONING DATA. MEAN ABSOLUTE ERROR AS A FUNCTION OF AZIMUTH POSITION: A. POSITIONING IN RANGE; B. POSITIONING IN ALTITUDE

in the setting and may also improve accuracy of superpositioning.

If our primary concern were psychophysical methodology, it would be interesting to pursue this point and attempt to clarify the situation by additional superpositioning experimentation. Since our primary interest is the display, it was considered more fruitful to continue related experimentation with a different technique. This is reported in the next section.

4.0 Experiment II: Resolution of Point Targets in a 3-D Display

Display resolution may be defined as the smallest distance between two point targets which allows an observer to detect the presence of the second target. In defining resolution in this way, rather than by the use of more conventional acuity-measuring devices, such as the fineness of detail in a test pattern, consideration was given to the uses of a display, such as the one under study, where awareness of the presence of a partially obscured target might be of greater importance to the operator than his ability to perceive the fine, sharply separated, gradations in a grid. Thus, resolution becomes a psychophysical variable rather than a characteristic of the device alone and a psychophysical experiment was performed to determine this kind of display resolution.

A point target is, of course, an abstraction; targets in the present study were 1/16" in diameter. Judgments of the presence of two targets could thus be made when the targets were distinctly separate, and also when the targets were overlapping. This type of judgment yields the desired detection threshold, rather than one for two-point separation.

4.1 Procedure

Resolution as defined above was studied in three dimensions using a method of constant stimuli. A standard target (St), fixed in location, was paired with a comparison target (Co), which could be located at any one of four distances from St, in any of 3 dimensions: range, altitude, and azimuth. It could also be superimposed on St in range and altitude and separated in azimuth by a distance, never perceptible, approximately 1/5 of the width of the pulse itself, or 0.1°. This gave rise to 13 possible pairings of St and Co.

These 13 combinations were presented to the subject 10 times each in a randomly arranged series of 130 trials at each of 8 azimuth positions, at mid-range and altitude. Targets remained in the display until the subject responded, whereupon they were removed until the start of the next trial.

At the start of a series, the Co was separated from the St a given distance in a given dimension, according to the random arrangement, and presented on the display. The subject responded with a judgment of superposition or separation. If he judged that the targets were separated, he was required to say in which dimension. The targets were then removed from the display, the information recorded, and the Co moved to the next position specified by the random order. Movement of the Co took place while it was blanked from the display and was never seen by the subject. When the 130 trials were completed, the St was moved to another azimuth position, and the procedure repeated.

4.2 Results and Discussion

The proportion of times two targets were perceived was obtained as a function of inter-target distance. This yielded a psychophysical function for each dimension in each azimuth position. A typical example of such a function is shown in Figure 4-1. A threshold was obtained from these functions in the three dimensions by the Spearman distribution method. This was considered a measure of display resolution, the smallest inter-target distance necessary for the detection of a second target.

Figure 4-2 is a polar coordinate plot of the mean threshold as a function of azimuth angle. The data was combined for the two subjects. The results are plotted separately for each dimension. The most striking aspect of this plot is the different effect of azimuth position on resolution in azimuth itself and in the two other dimensions. Resolution in range and altitude varies in a fashion similar to accuracy of superposition in those dimensions; resolution in azimuth, however, varies in the opposite direction, although the variations are less marked. This result might be expected, since at 90° and 270° targets separated in range and altitude lie in the same plane as the subject's line-of- sight and and therefore are seen binocularly at very small visual angles. When targets are separated in azimuth at these locations, however, the Co is not directly along the observer's line-of-sight while the St is. The smaller varibility due to azimuth is simply the result of the generally better viewing conditions at the locations at which, geometrically, azimuth resolution is poorest, i.e., at 0° and 180°.

Figure 4-3 is a linear plot of the data with the results for each Subject shown separately. Inter-subject varibility is very small in range and altitude; it is somewhat greater in azimuth. However, even here, the differences are more in degree than in direction, one subject being consistently better than the other, and the functions are quite similar in shape. In fact, a Sign test showed no significant differences between subjects.

The absolute magnitude of target resolution is relatively small, being less than a tenth of an inch, except at 90° and 270°. Moreover, the decrement at these locations may be easily overcome by moving the head so that the target is a few degrees away from these positions, as was shown in the previous study on target superposition. These bracketing measures were not repeated because of the general compatability of results of the two experiments.

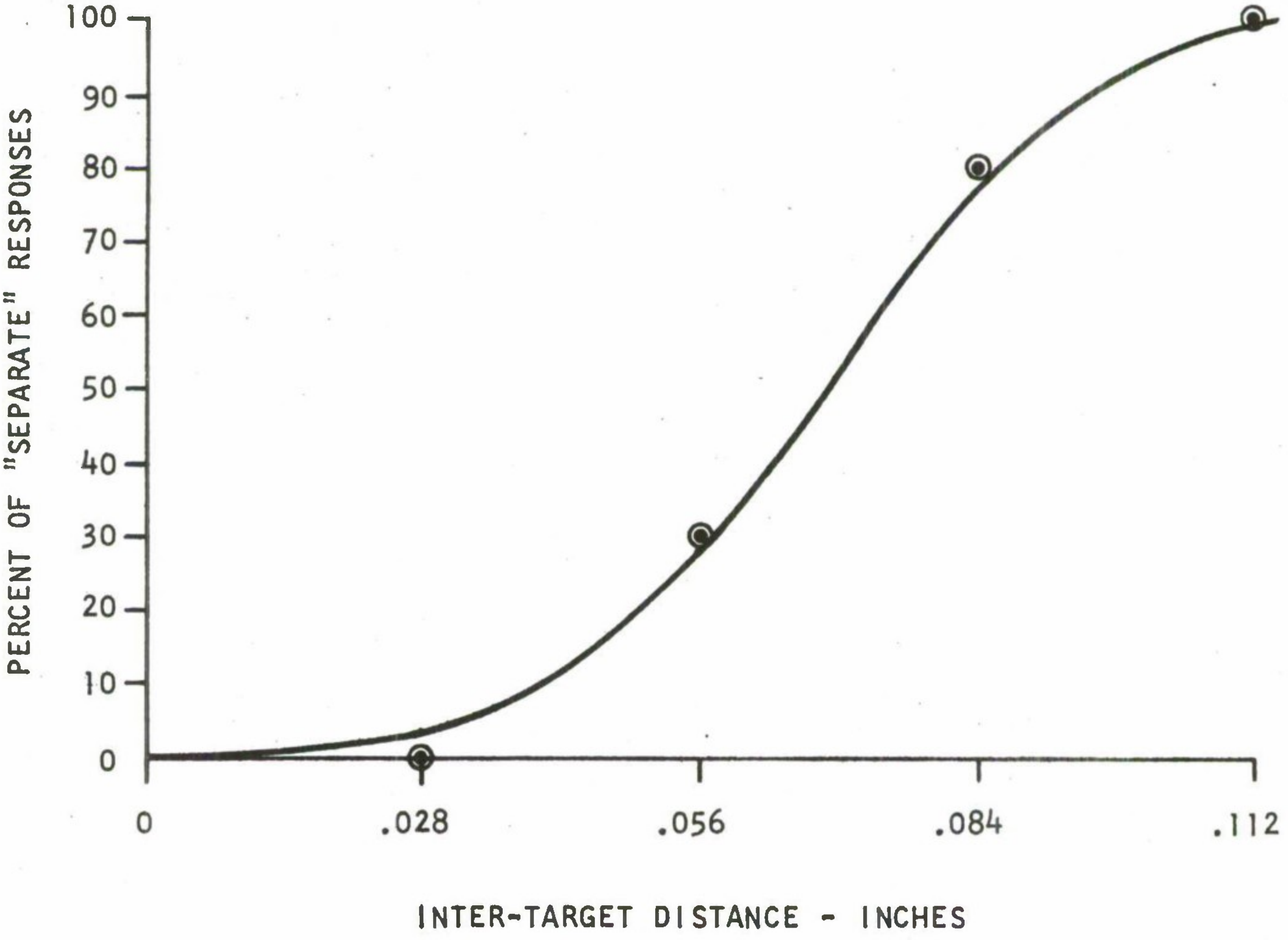

FIGURE 4-1

TYPICAL PSYCHOPHYSICAL FUNCTION
PERCENT "SEPARATE" RESPONSES AS A FUNCTION OF TARGET SEPARATION IN ALTITUDE FOR ONE SUBJECT (M.K.) AT AN AZIMUTH ANGLE OF 45°

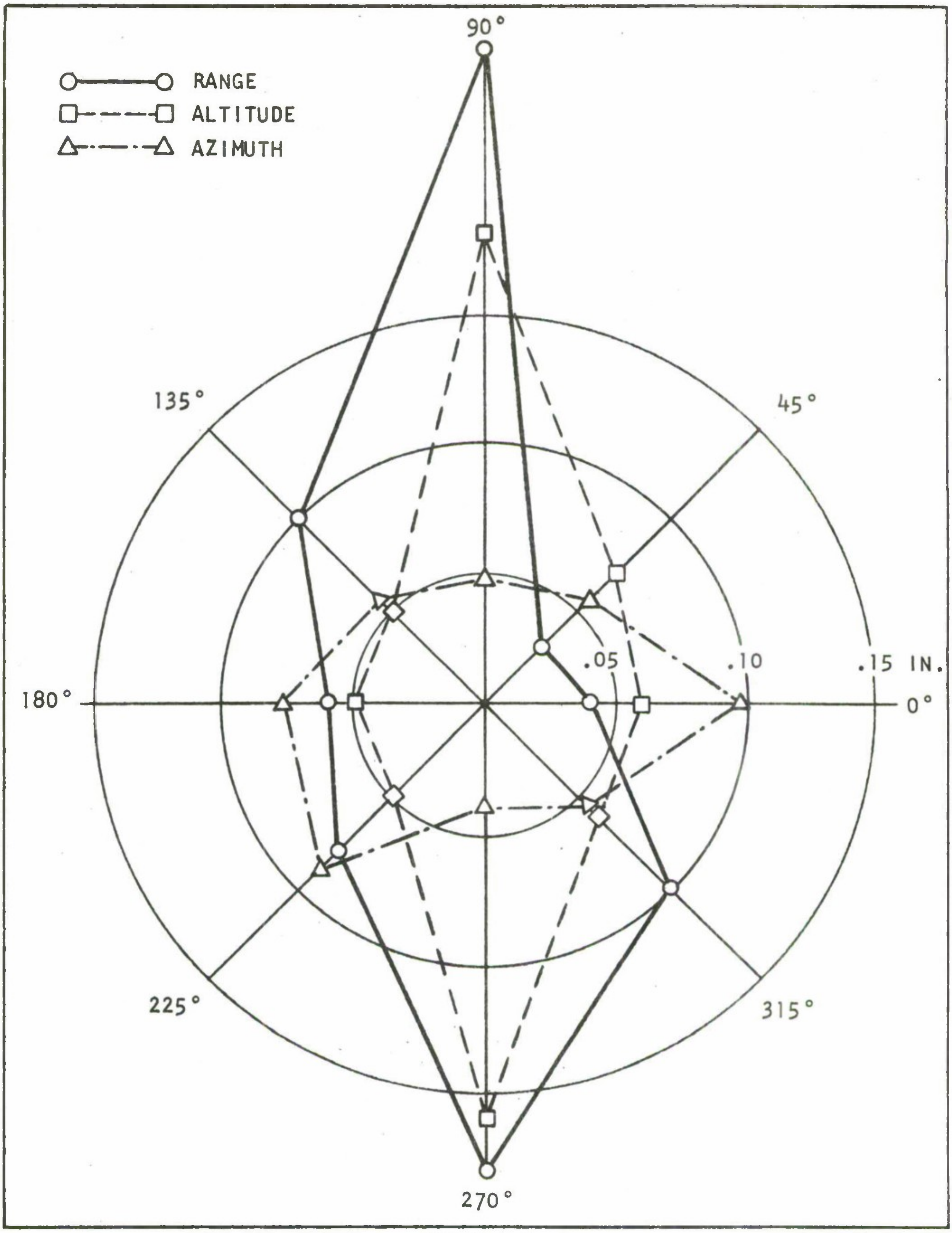

FIGURE 4-2

RESOLUTION IN RANGE, ALTITUDE AND AZIMUTH AS A FUNCTION OF AZIMUTH ANGLE

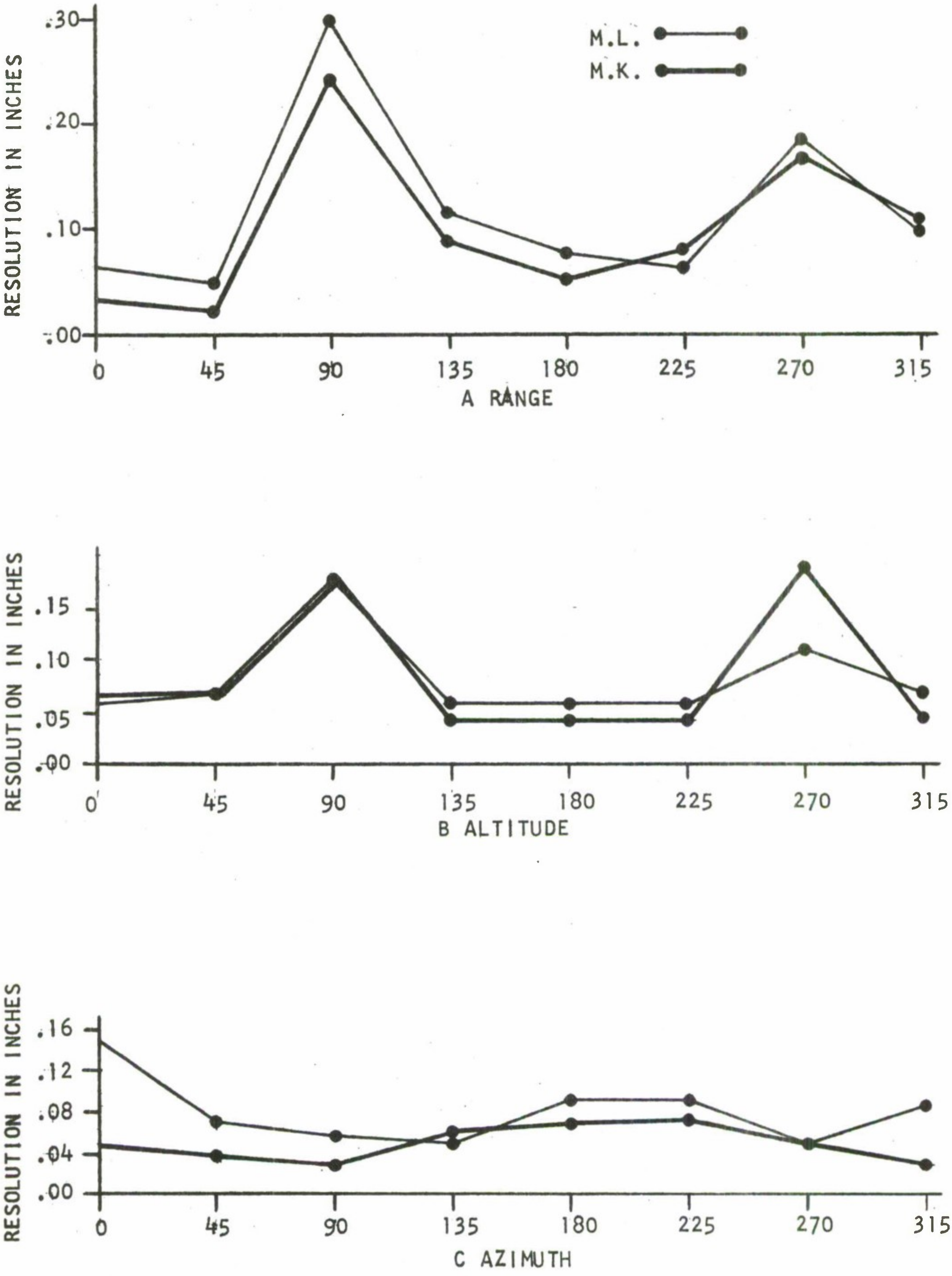

FIGURE 4-3

RESOLUTION IN RANGE, ALTITUDE AND AZIMUTH
AS A FUNCTION OF AZIMUTH ANGLE

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When a judgment of separation was made, the accompanying judgment of the dimension of separation was very seldom in error. Therefore, the proportion of direction errors associated with "separate" judgments was obtained for both subjects, combined over inter-target distance as a function of azimuth angle, and combined over azimuth angle as a function of inter-target distance. The former is shown in Figure 4-4. The pattern of error follows the general pattern of resolution as a function of azimuth angle, especially in range, where errors are most frequent. The pattern is less discernible is altitude and azimuth, probably because of the lesser frequency of errors. The higher error frequency in range may be explained by the fact that range differences may be differences in depth at certain positions and, at others, may appear to be azimuth differences due to the slight angle at which they are viewed when the subject's line-of-sight is aligned with the center of rotation. This is borne out by an examination of the types of errors made. Errors in identifying range differences at 90° and 270° are almost always confusions with altitude differences while, at 45° and 225°, range differences are mistaken for differences in azimuth.

Figure 4-5 presents the proportion of errors as a function of inter-target distance. This is expressed in terms of the four distances between the St and Co targets which comprise the abscissa values of the psychophysical functions described above. The actual values in inches, though equally spaced, would, of course, be different under each of the conditions studied. In combining them, therefore, they are simply ranked in increasing order of distance between St and Co targets. As would be expected from such a relationship, errors decrease as inter-target distance increases. This is more marked for range, where errors are more frequent, than for altitude or azimuth. More notable, perhaps, than the relation between error proportion and distance is the generally small error. The highest proportion is only .33, while even the small increments used to study threshold decrease error markedly. Part of this is due to the fact that equipment limitations sometimes prevented the use of intervals small enough to cover the threshold transition zone without producing a step-function, so that the larger distances (3 and 4) occasionally produced 10 responses of "separate". However, this was not true for the smaller distances (1 and 2). It must be remembered that these proportions are based on the total number of target pairs judged "separate", not on the total number of target pairs judged. It may therefore be concluded that, when an observer can perceive a separation between targets, even one very close to separation threshold, he can perceive the direction of separation with a high degree of accuracy.

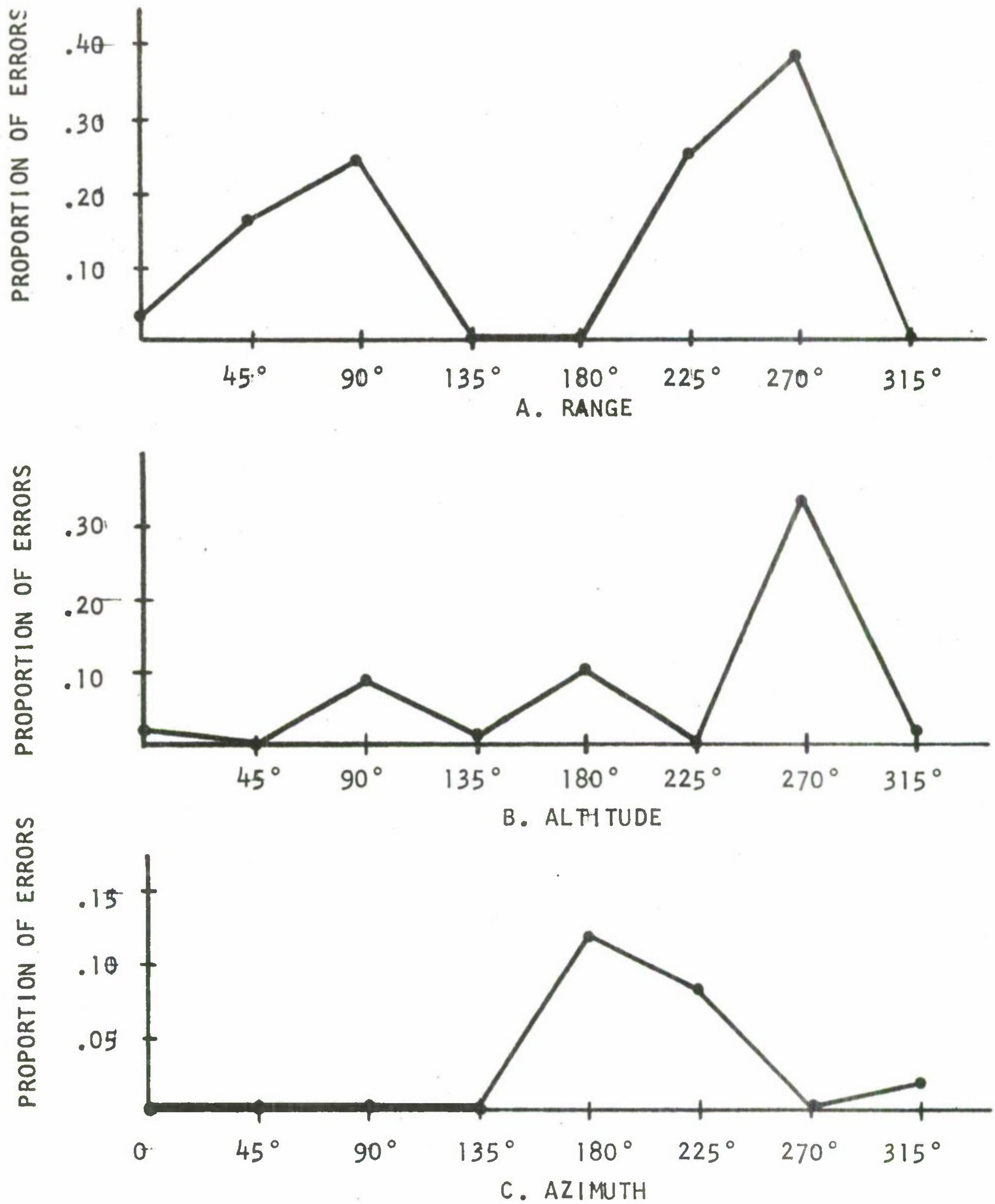

FIGURE 4-4

PROPORTION OF ERRORS IN JUDGEMENT OF DIRECTION ASSOCIATED WITH "SEPARATE" RESPONSES AS A FUNCTION OF AZIMUTH ANGLE.

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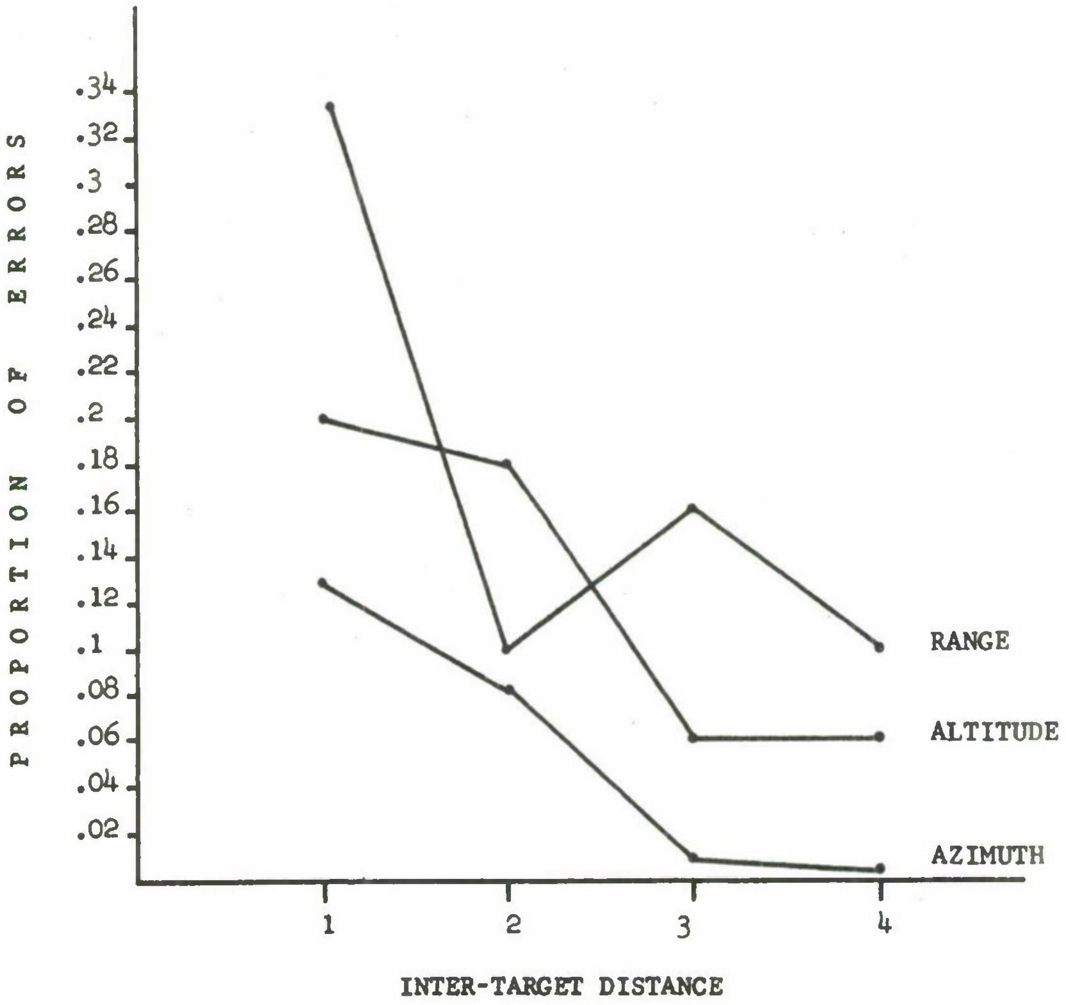


FIGURE 4-5. Proportion of Errors in Judgment of Direction associated with "Separate" Responses as a Function of Inter-Target Distance.

In sum, display resolution varies with azimuth angle in a fashion similar to that of target superposition. The magnitude of separation necessary for the perception of 2 targets is again small, being approximately .02 - .08 inches at the best positions. Targets viewed along the line-of-sight require considerably greater separation for perception. However, the smaller values may be taken as representative, since the possibility of viewing the display from any angle makes viewing along a rigidly fixed line-of-sight unnecessary.

5.0 Experiment III. Location of Point Targets within the Display Volume Relative to the Display Boundaries

The purpose of this investigation was to obtain data concerning the accuracy with which point targets could be located within well-defined display boundaries. Constant errors in judgment as well as the reliability of repeated judgments were two measures of special interest. Since measures of "direct" perception of spatial relations were desired, a response method was chosen which avoided the use of cursors or other designation aids.

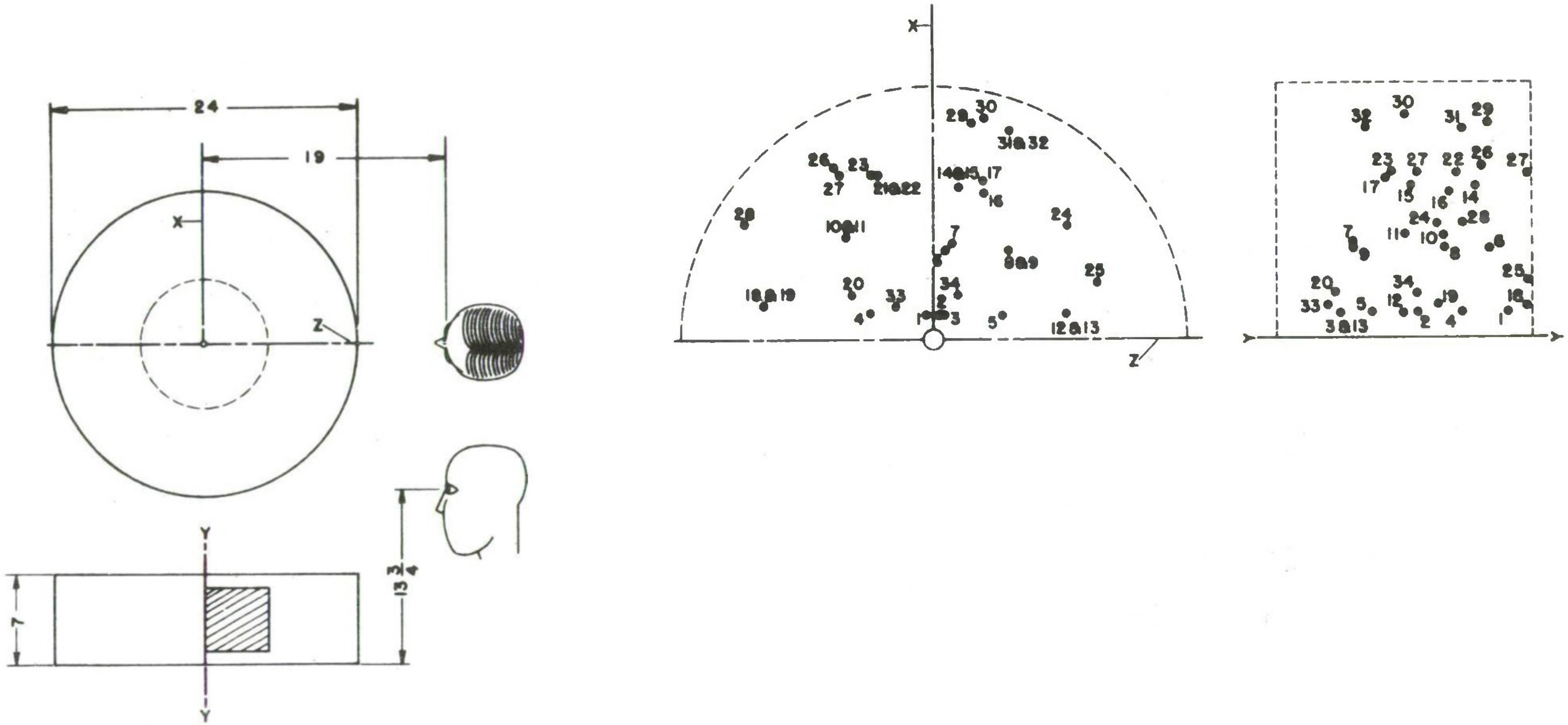
5.1 Procedure

The method used to investigate the perception of spatial relations required the observer to estimate the location of a point target by marking its perceived position on an appropriate set of scales (a PPI-type graph plus an altitude scale). The observer was thus required to make a direct judgment of where the target was with respect to the display boundaries. This judgment could then be quantified and compared in a variety of ways to the actual known position of the target.

Thirty-four target locations were selected for this experiment. Each target was approximately 0.06 inches in diameter and could be uniquely defined by its position within the display volume. For purposes of these definitions, the distance from the center of the display to the target is called X, and distance from the leading edge of the display (closest to the subject) to the target is called Z, and the distance from the bottom of the display to the target is called Y. Accordingly then, X and Z represent two measures of range and Y represents altitude. Table 5.1 lists all the targets and their locations as specified by X, Y and Z. The units of measurements are quarter-inches so that target number 1, for example, is one-half inch from the display center, twelve and one-eighth inches from the leading edge of the display, and one and one-quarter inches from the bottom of the display. Preliminary investigations showed no response bias between either half (left-right) of the display volume and all targets were therefore located on the right side. This enabled us to select a non-prohibitive number of different target locations. Figure 5-1 presents a front elevation and a plan view of the display volume and screen each of which shows the relative location of the subject. Also included in this figure are diagramatic representations of the point target locations used in this experiment. It can be seen that all targets were to the right of the center of the display and filled virtually all of the screen area.

TABLE 5.1 - POINT TARGET LOCATIONS
(See Text for Explanation)

Target No.	x	y	z
1	2	5	48.5
2	2	12	47.5
3	2	18	47
4	2	8.5	53
5	2	15.5	42.5
6	7	6.5	47
7	7.5	17	46.5
8	7	10	42
9	7	17	42
10	8	10	55
11	8	13	55
12	2	13	37.5
13	2	18	37.5
14	12	7.5	46
15	12	12.5	46
16	11.5	9.5	44
17	12.5	14.5	44
18	2.5	3.5	61.5
19	2.5	10.5	61.5
20	3.5	18.5	54.5
21	13	3.5	52.5
22	13	9	52.5
23	13	14	53
24	9	10.5	37.5
25	4.5	3.5	35
26	13.5	7	56
27	13	12	55.5
28	9	8.5	63
29	17	6.5	45
30	17.5	13	44
31	16.5	8.5	42
32	16.5	15	42
33	2.5	19	51
34	3.5	12	46



X - WIDTH FROM CENTER LINE
Y - HEIGHT FROM BASE LINE
Z - DEPTH FROM LEADING EDGE DISPLAY BOUNDARY

FIGURE 5-1.
POINT TARGET LOCATIONS RELATIVE TO SCREEN AND OVERALL DISPLAY BOUNDARIES

Each of the thirty-four targets was presented five times to each subject, making a total of 170 trials. Two separate sessions, twenty-four hours apart and consisting of 85 trials, were held. A random order of presentation for the first subject was constructed and was simply reversed for the second subject so that the latter's last trials was the former's first.

For each trial the subject had a specially prepared response sheet on which he was to indicate the location of the target. The response sheet had a vertically oriented line and a circle with a dot at the center. The altitude of the target was to be indicated by a slash mark across the vertical line; the range from the center and from the leading edge of the display volume was to be indicated by a single dot placed in the circle. The subject was instructed to interpret the line and circle as representing the external boundaries of the display volume and locate the target accordingly. Rate of target presentation wa subject-determined and a five-minute rest period was taken in the middle of each session.

5.2 Results and Discussion

In order to interpret the results of this experiment, it was first necessary to convert the pictorial responses of the subjects into quantitative terms. This was easily done through the use of an overlay which permitted direct conversion into appropriate (non-scale) values of x, y and z.

The overall response error is described as the distance between the presented target and the perceived target (response). If we describe the target as a point in space having location (x_t, y_t, z_t), and the response as point having location (x_r, y_r, z_r), then the distance between these two points is defined as:

$$\text{distance (D)} = \sqrt{(x_t-x_r)^2 + (y_t-y_r)^2 + (z_t-z_r)^2}$$

It should be noted that this overall error term contains three components errors, each with respect to a single axis of the three-dimensional space. These component errors may be derived, as indicated, from simple subtractions of the respective target and response locations. This method utilizes the recti-linear coordinate system centered about the display boundaries. For our purpose, however, it was decided to calculate the component errors using a coordinate system based on the line-of-sight between the subject and the target. Specifically, the following method was employed. First, a plane normal to the line-of-sight at the target is found. The distance between the response and this plane represents the z component error and is calculated as follows:

$$E_Z = \frac{A_{x_r} + B_{y_r} + C_{z_r} + D}{A^2 + B^2 + C^2}$$

where A, B, C, .are direction numbers of the plane and x_r, y_r and z_r represent the location of the response. Figure 5-2 illustrates the geometry of this solution. Note that d_z, in the figure, represents the z component error between the target and response when the display-oriented rectangular coordinate system is considered. To find the y component error, a second plane is derived which is normal to the first, passes through the line-of-sight, and extends laterally to the left and right. Reference to Figure 5-2 again shows the geometric solution for this error component, E_y. The x component error, E_x, is found by calculating the distance from the response point to a third plane which is perpendicular to the first two and extends up and down through the line-of-sight. To summarize, the extraction of error in a response is based on a coordinate system whose three orthogonal axes are centered about the line-of-sight and whose origin is the presented target location. Obviously, then, a different coordinate system is used for each target, and the error in a response is measured relative to its associated target. The formula for overall error, D, can now be rewritten simply as:

$$D = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

Table 5.2 contains the mean overall error (D) for each subject on each target. In order to get some idea of inter-subject differences, the distance between the subjects responses was also calculated. This statistic D^1_{JL-MK} disregards the two target locations and simply measures the difference between the two subjects' responses. The overall mean difference between subjects was found to be 4.26 quarter-inches. Comparing this to the subjects' overall D's of 4.16 and 4.26 it appears as if they are, on the average, as far from each other as they are from the target. A logical conclusion from this, that large individual differences were present, was further checked by correlating the subjects' overall error scores. This condition is found to be +.07. Correlations were also calculated between the mean algebraic component errors (E_x, E_y, and E_z) on the thirty-four targets and were found to be:

$$r_{E_x E_x} = +.13$$

$$r_{E_y E_y} = +.79$$

$$r_{E_z E_z} = +.13$$

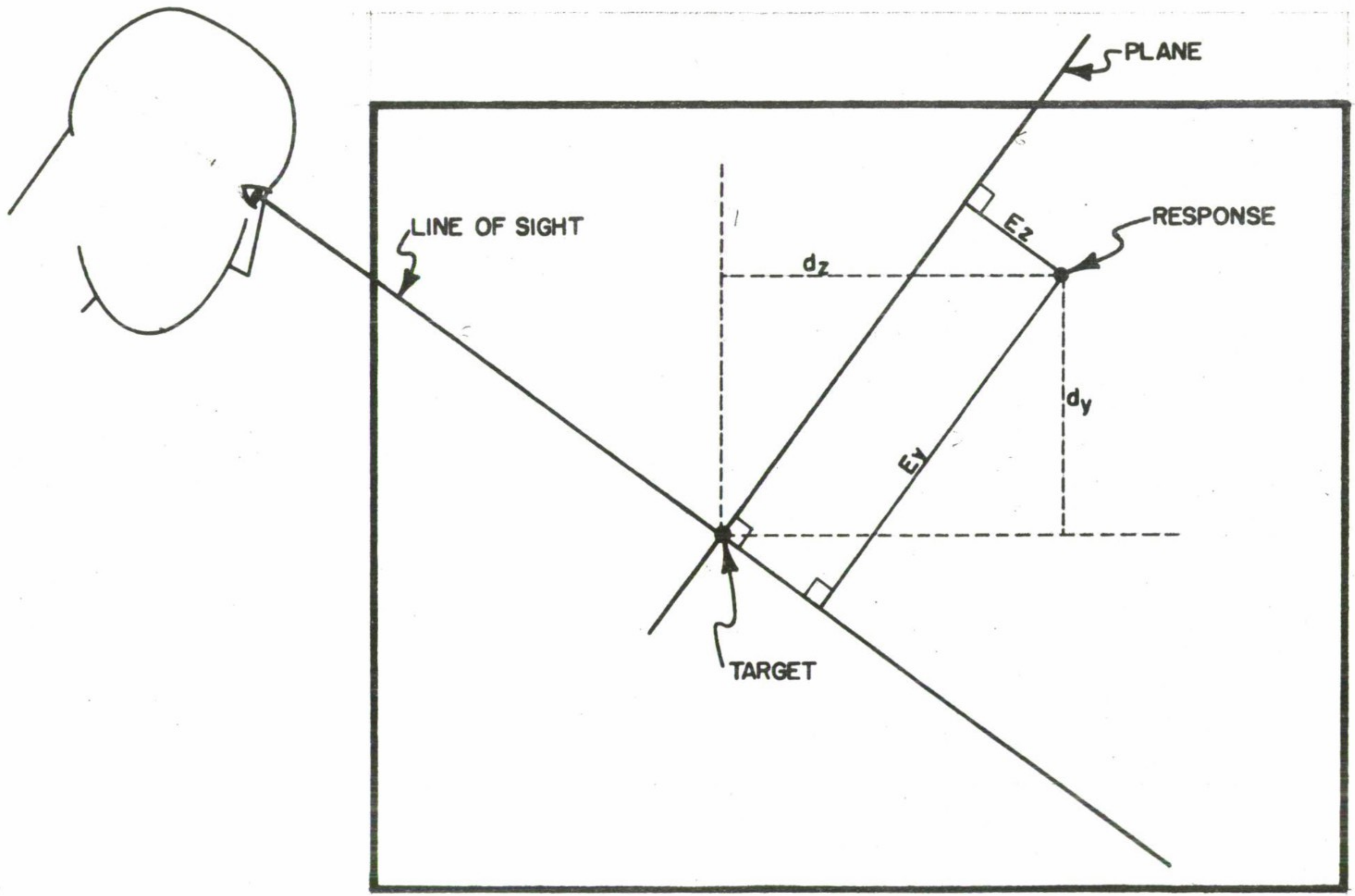


FIGURE 5-2. GEOMETRIC SOLUTION FOR E_y AND E_z

TABLE 5.2. MEAN DISTANCE BETWEEN POINT TARGET LOCATION AND PERCEIVED LOCATION.

(Table entries are in quarter-inches)

	$\bar{D}_{JL}$	$\bar{D}_{MK}$		$\bar{D}_{JL}$	$\bar{D}_{MK}$
1	4.48	3.62	18	5.24	2.78
2	3.86	2.56	19	4.84	4.14
3	3.55	3.00	20	6.54	3.50
4	1.90	3.00	21	4.66	3.52
5	5.18	4.86	22	4.96	4.68
6	3.05	3.23	23	5.92	3.06
7	4.20	4.12	24	3.14	5.24
8	2.14	3.78	25	3.28	5.48
9	3.46	4.08	26	4.60	3.52
10	2.88	3.78	27	5.49	4.23
11	4.96	3.10	28	4.64	5.02
12	3.90	6.04	29	3.98	6.76
13	5.94	6.34	30	2.36	4.92
14	3.70	6.26	31	3.48	5.30
15	3.57	2.99	32	3.34	6.44
16	2.46	3.85	33	7.58	4.94
17	4.96	4.54	34	2.66	2.16
			OVERALL	4.16	4.26

Thus, the altitude (y) component error is found to be highly similar between the two subjects but the left-right range (x) and fore-aft range (z) component errors are dissimilar.

An important question to be answered by this experiment concerns the relation of target location to the response error. Table 5.3 contains the relevant correlations. Since we have already established that the subjects' responses were unrelated, the analysis is performed separately on each subject. Care should be taken in assigning meaning to the sign of the correlation coefficients. Since the component error means for each target are derived algebraicly, they may be positive or negative. A positive mean component error indicates that the direction of error is, on the average, towards the origin of the respective axis. Thus, a positive x component error means that the target is generally displaced towards the center of the display (towards the left); a positive y component error indicates that the target is displaced upwards; and a positive z component error indicates target displacement towards the subject. Negative component errors, of course, indicate response displacement in the opposite direction. Referring to the table now, a positive correlation involving a component error means that as the location recedes from the coordinate system origin the error becomes increasingly positive and a negative correlation means that the error becomes increasingly negative. Thus, magnitude of the error is not necessarily reflected by the sign of the correlation.

As can be seen from inspection of Table 5.3, the location of a target does appear to be related to the error made in judging its position. In general, however, the effects of location are different between the subjects. The only exception to this is the effect of the target location with respect to y axis on the y component error, E_y. These results are in accord with the data reported earlier which indicates that the subjects' response errors are not related except for the y component error. It is of special interest to note that the differences between subjects as shown in Table 5.3 not only relate to the amount of dependence on location, as indicated by the different magnitudes of associated correlations, but, also to the direction of error. These results lead directly to the conclusion that although target location generally appears to be related to response error, there is a strong interaction with individual characteristics of the observer. Further study of these individual differences is certainly indicated, but is beyond the scope of the present study.

The primary reason for using line-of-sight coordinate systems for analyzing the response errors was the hypothesis that, in general, the errors

TABLE 5.3. CORRELATIONS BETWEEN TARGET LOCATION AND RESPONSE ERROR

		SUBJECT JL				SUBJECT MK			
		E_x	E_y	E_z	D	E_x	E_y	E_z	D
Stimulus Position	x	*** -.58	-.24	-.08	-.16	* +.30	-.26	* -.30	* +.32
	y	+.13	*** +.79	-.24	* +.34	-.02	*** +.89	* -.31	+.06
	z	+.07	* -.31	-.22	* +.37	** +.46	-.25	*** +.74	** -.47

* $p < .05$
** $p < .005$
*** $p < .0005$

made would be related to the line of sight. Thus, it was hypothesized the y and z component errors would be related such that the integrity of the line of sight would be maintained. That is, if a response located the target beyond its true position (i.e., a positive z component error was made), the response would also locate the target below its true position (i.e., a negative y component error would be made). The opposite tendency was also hypothesized. A chi-square test supported this hypothesis (X^2=25.26, $p < .001$). A corollary of this hypothesis is that x component errors will be smaller than y or z component errors. This follows since x component errors would result in the target being displaced off the line of sight without chance of compensation, whereas y and z component errors have been shown to be mutually compensatory. This corollary is tested by utilizing absolute mean component errors and is supported

$$(\left[E_x\right] = 1.33, \quad \left[E_y\right] = 2.40, \quad \left[E_z\right] = 2.51).$$

One aspect of the data which has not been dealt with concerns the amount of constant error or systematic bias in the responses. Table 5.4 shows the proportion of component scores which were negative and were positive. It can be seen that a negative constant bias in the z component error for both subjects is present, i.e., there is a strong tendency for both subjects to displace the target towards the origin of the z axis (leading edge of the display). This, together with the fact that no strong bias is present in the y component error, would tend to mitigate against the line of sight hypothesis presented above. The highly significant corroboration of that hypothesis is therefore even more impressive. With respect to the x component error, the opposite biases shown by the two subjects explains, at least in part, the fact that correlations between target location and z component error tended to be in opposite directions for the two subjects (see Table 5.3). Although Table 5.4 shows direction of bias, it does not indicate the magnitude of the bias. This data is presented in Table 5-5. As can be seen from inspection of this table, the magnitude of the constant error for the z component error is large enough to contribute substantially to the total error as represented by the absolute mean component errors presented above. For subject JL, 83% of the total z component error can be attributable to constant error, and for Subject MK, 69% of the z component error is attributable to constant error. For Subject MK, 55% of his x component error is attributable to constant error. In no other case does the constant error contribution exceed 12%.

TABLE 5.4. PROPORTION OF POSITIVE AND NEGATIVE COMPONENT ERRORS
(Zero errors not included)

	JL		MK		Both	
	+	-	+	-	+	-
E_x	.42	.58	.65	.35	.53	.47
E_y	.58	.42	.54	.46	.56	.44
E_z	.14	.86	.21	.79	.17	.83

TABLE 5.5. DIRECTION AND MAGNITUDE OF CONSTANT ERROR FOR EACH SUBJECT

	$\bar{E}_x$	$\bar{E}_y$	$\bar{E}_z$
JL	+0.16	+0.31	-2.08
MK	+0.73	+0.13	-1.72

6.0 Experiment IV. Absolute Threshold for the Perception of Motion

Two experiments were performed to investigate the perception of target motion. The first, reported in this section, involves the determination of the absolute threshold of motion under various conditions of distance traversed by a target, ambient illumination, target location and direction of motion. The second experiment, reported in Section 7.0, is concerned with the relative motion threshold, the perception of differences in rate of linear motion.

In designing the experiment reported here, it was assumed that data concerning the direct perception of motion would be more relevant to the display evaluation and more practically useful than data on the inference of motion. We asked our observer to report whether a target appeared to be moving, not whether, using various cues, he could deduce that it had moved. This, of course, imposed a difficult judgmental task and it is by no means claimed that the data presented here are free of the influence of inferred motion. However, to the extent possible, the judgments do reflect the observer's direct perception of motion. One indication that the observers had some success in maintaining the desired criterion is evidence (to be presented) that a lower threshold can be achieved for inferred motion.

6.1 Procedure

The absolute threshold for the perception of motion was determined under seven experimental conditions, defined in terms of target azimuth, extent and direction of target motion, and ambient illumination. The seven combinations selected for study are indicated (by X) in the following table.

TARGET AZIMUTH	TARGET MOTION		AMBIENT ILLUMINATION AT DISPLAY		
			RED		WHITE
	DIRECTION	EXTENT	5.1 Ft. L.	35 Ft. L.	11 Ft.L.
0°	Horizontal	0.25"	X	X	X
		0.50	X		
		1.00	X		
	Vertical	0.25	X		
90°	Horizontal	1.00	X		

The five conditions involving horizontal motion at 0° azimuth are selected to yield a general indication of the effects of extent of motion and ambient illumination. The remaining condition at 0° provides a comparison between horizontal and vertical motion. The last condition, involving horizontal motion at 90°, provides a comparison between the 0° and 90° azimuth positions. The choice of a 1.00 inch extent of motion for the 90° azimuth case was based on consideration of the geometry of the situation. A horizontal motion of 1.00 inch at 90° subtends a visual angle of 50', not too dissimilar in angular extent to the approximately 40' subtended by the 0.25 inch motion at 0°. Thus, a comparison between conditions roughly comparable in terms of visual angle is available; of course, the 1.00 inch case at 0° provides a direct comparison of the two azimuth positions in terms of equal linear extent of motion.

For horizontal motion the target moved in or out in range along the mid-altitude line. Target motion started 1.5" from the center of the display for motion away from the center. For motion toward the center, the motion started at (1.5 + E)", where E is the programmed extent of target motion. Thus, motion toward the center always terminates at 1.5" from the center. This arrangement was selected to minimize the separation between initial and terminal positions for the two directions of motion, thus minimizing the basis for judgments due to position only (without regard to the perception of motion). Also, for the target presentations entering into each threshold determination which differ from one another only in velocity (or time to traverse the fixed extent), discrimination of position is effectively held constant as a basis for the judgment of motion. That is, a judgment based on position is dependent on initial position only and should not be a function of the velocity of the subsequent target course.

For vertical motion, the target moved up or down along a vertical line 1.5" from the center of the display. In a manner analagous to that described for horizontal motion, the upward target course started 0.25" from the bottom of the screen and the downward target course terminated at this point.

A method of constant stimuli was used to determine the threshold of motion. Under each experimental condition, the target velocities were selected to cover the transition zone around the subject's threshold of motion. Each of these velocities was presented ten times for a total of 100 trials per condition. On half the trials for a condition, targets moved in one direction; on the other half, they moved along the same path in the opposite direction. The subject was required to respond with a judgment of "moving" or "still" and also to state in which direction the target had moved. The order in which the target velocities were presented as well as the direction of motion was randomized.

The observer viewed the display from the standard viewing position through an oscilloscope hood mounted in an opaque screen which controlled his viewing position and limited his field of view to the display volume and its immediate surround. An experimental session consisted of the 100 trials of one experimental condition. A short rest period was given after the first 50 judgments. On each trial, the experimenter introduced a point target in accordance with his predetermined schedule; the target appeared in the display, travelled its prescribed course and disappeared, and the observer made judgments of motion and direction of motion.

6.2 Results and Discussion

Psychophysical functions were plotted for both subjects under all conditions on linear and on probability coordinates ("Probit" paper). Thresholds were estimated from a straight line fitted by eye to the probability function and, as a check on this method, were computed by the Spearman distribution method. The thresholds obtained by the two methods of analysis are presented in Table 6-1. The entry on the left of each cell is the threshold in inches per second; that on the right is the same threshold in minutes of visual angle per second. It will be noted that both methods yield almost identical thresholds, the largest difference being only .005 inches per second, or .6 minutes of arc per second. Therefore, the remainder of the discussion will be concerned only with thresholds obtained by interpolation from the probability functions.

TABLE 6.1

Threshold of Motion in inches per second and minutes of visual angle per second, obtained by two methods of estimation

INTERPOLATION FROM "PROBIT" PLOT

CONDITION	SUBJECT	EXTENT OF TARGET MOTION 1/4 inch		1/2 inch		1 inch	
Low red ambient	ML	.071	10.7'	.043	6.4'	.031	4.6'
Horizontal motion	MK	.054	8.1'	.050	7.5'	.031	4.6'
High red ambient	ML	.043	6.4'				
Horizontal motion	MK	.041	6.1'				
White ambient	ML	.043	6.4'				
Horizontal motion	MK	.022	3.3'				
Low red ambient	ML	.052	7.8'				
Vertical motion	MK	.020	3.0'				
Low red ambient	ML					.24	12'
90° horizontal	MK					.18	9'

SPEARMAN DISTRIBUTION METHOD

CONDITION	SUBJECT	EXTENT OF TARGET MOTION 1/4 inch		1/2 inch		1 inch	
Low red ambient	ML	.068	10.2'	.044	6.6'	.032	4.8'
Horizontal motion	MK	.049	7.5'	.049	7.5'	.035	5.2'
High red ambient	ML	.042	6.3'				
Horizontal motion	MK	.042	6.3'				
White ambient	ML	.047	7.0'				
Horizontal motion	MK	.025	3.8'				
Low red ambient	ML	.054	8.1'				
Vertical motion	MK	.020	3.0'				
Low red ambient	ML					.24	12'
90° horizontal	MK					.20	10'

The data in Table 6-1 which relates to extent of target motion is plotted in Figure 6-1. This figure shows the threshold for target motion (minutes of arc/sec) as a function of target excursion (inches). For each observer, the motion threshold decreases as extent of motion increases from 0.25 inches to 1.00 inches. Over this four-fold increase in linear extent of motion, the threshold decreases by a factor of roughly two. This effect does not appear to be directly attributable to the extent of motion. Subjects were required to state the direction of motion as well as whether or not the target appeared to be moving. It was found that the observer could correctly report direction of motion at rates below those at which he reported perception of motion. As shown in Table 6-2, over the entire range of stimulus values used for determining the perceived rate of motion, few errors in judged direction of motion were made with the 0.25 inch target excursions, fewer still at 0.5 inches, and almost none when the target moved 1.00 inch. Table 6-2 also shows that over the range of stimulus values (target rates of motion) extending well below the threshold for directly perceived motion, there is only a moderate increase in the frequency of error in direction judgment. Apparently the threshold of direction of motion lies well below the threshold for directly perceived motion.

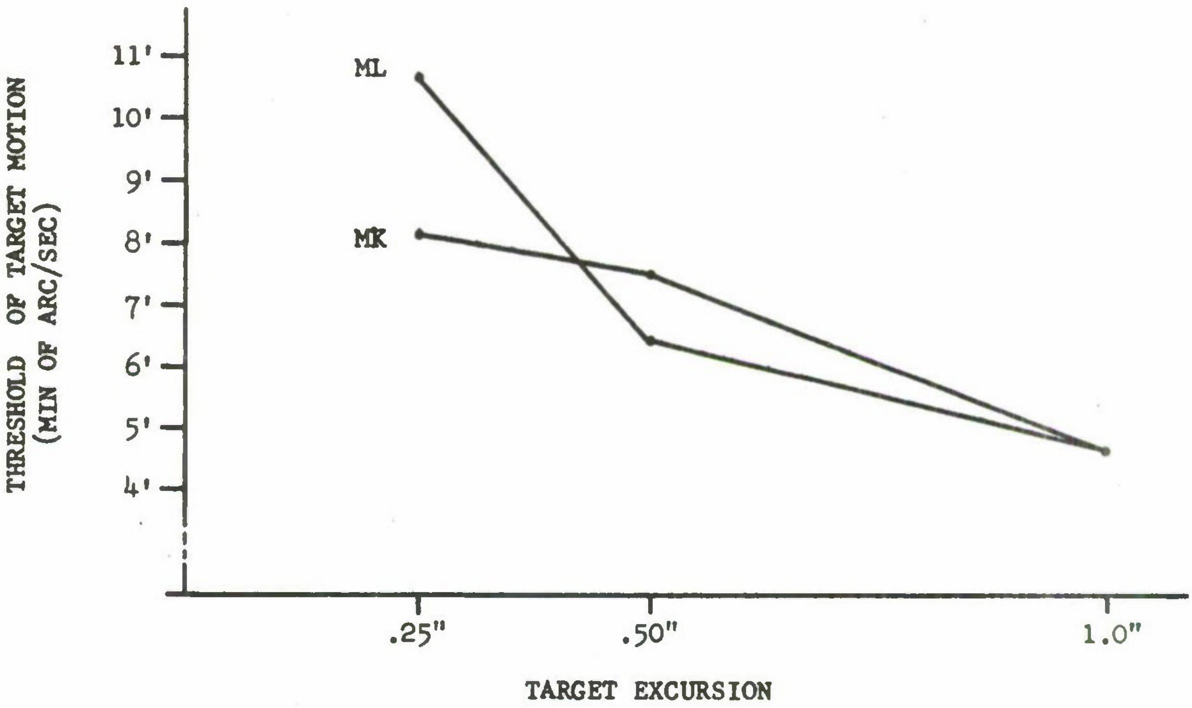


FIGURE 6-1. Threshold of target motion as a function of target excursion.

TABLE 6.2

Number of errors in 10 trials in stating direction of motion as a function of experimental conditions and stimulus velocity values

Subject: ML

	STIMULUS VALUE										
	below threshold							above threshold			
CONDITION	1	2	3	4	5	6	7	8	9	10	SUM
1/4" hor. low red	3	1	2	2	3	2	2	0	0	0	15
1/2"	3	3	0	1	0	0	1	0	0	1	9
1"	-	1	1	1	1	0	0	0	0	0	4
1/4" hi red	1	2	2	1	2	4	1	2	0	3	18
1/4" white	2	2	0	0	1	2	1	1	0	0	9
90°	1	0	1	0	1	1	0	4	1	1	10
vertical	4	4	4	4	1	1	2	2	3	2	27
SUM	14	13	10	9	9	10	7	9	4	7	

Subject: MK

CONDITION	1	2	3	4	5	6	7	8	9	10	SUM
1/4" hor. low red	4	2	1	2	2	4	1	0	2	1	19
1/2"	5	1	1	0	0	1	0	0	1	0	9
1"	-	0	0	0	0	0	0	0	0	0	0
1/4" hi red	1	0	3	3	0	3	1	1	1	2	15
1/4" white	2	1	3	1	3	1	2	0	0	4	17
90°	1	0	0	0	0	1	0	1	1	0	4
vertical	-	1	4	2	4	2	2	2	0	2	19
SUM	13	5	12	8	9	12	6	4	5	9	

Since the threshold for direction of motion must be based on inferences or perceptions concerning the extent of motion, it may be concluded that extent of motion attains its maximal effect on motion thresholds well below the level of the present data. If this is correct, an alternative explanation must be adduced to account for the decrease in motion threshold with increase in extent of motion which is shown in Figure 6-1. One possibility, which also cannot be confirmed by the present data, is that the increase in extent acts indirectly by increasing the time available for the perception of motion. It may be noted that the rate of decrease in threshold is not rapid enough to maintain a constant duration of excursion at threshold, i.e., trial length continues to increase.

The effect of ambient illumination is most easily seen in Figure 6-2. The red illumination came from two incandescent lamps whose brightness was controlled by a Variac from outside the test room, and whose color came from red cellophane filters. These were placed behind the subject as shown in Figure 2-1. Under the lower red illumination, any parts of the display which might serve as a frame of reference, such as the center of rotation, were invisible. They were made somewhat more obvious by the higher red illumination. The white light, however, came from ceiling fixtures above the display and thus increased the visibility of those parts of the display, especially the center of rotation, which might serve as a source of reference. Thus, the abscissa of the plot in Figure 6-2 is an ordinal scale of increasing effective display illumination.

It can be seen, then, that increasing the effective ambient illumination in the display decreases the threshold of motion, probably as a result of making visible the stationary parts of the apparatus. The two subjects, however, differ somewhat in their response to changes ambient illumination. Both have lower rate thresholds at higher ambient levels; Subject ML, however, exhibits no further decline in threshold after the initial increase in illumination. The comments of the subjects may shed some light on this; ML commented that the center of rotation (the most evident fixed reference) was clearly visible under high red illumination, while it was not clearly visible to MK. At any rate, this seems to be an individual difference, and does not invalidate the conclusion that threshold of motion decreases as ambient illumination increases. Perhaps further elaboration of the illumination conditions would show two functions which differed only in the point at which further increase in ambient illumination produced no further decrease in threshold of motion.

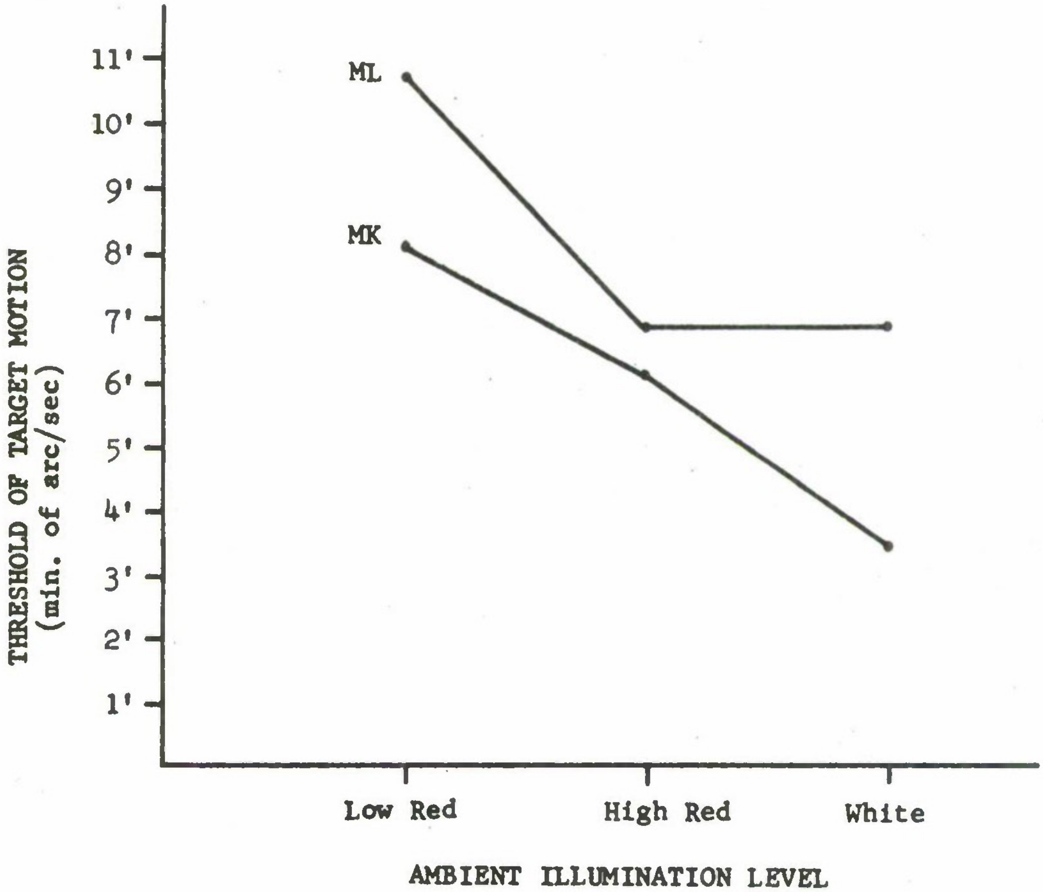


FIGURE 6-2. Threshold of target motion as a function of effective level of ambient illumination.

It remains to be said that, while the effect of illumination level is significant, it is not large in an absolute sense, and low ambient levels can be easily tolerated if they are necessary for other reasons.

A threshold for vertical motion of 1/4 inch extent was also obtained, and is presented in Table 6-1. Both subjects show a marked decrease in threshold for vertical motion. This single determination provides little basis for attempting to infer the reason for the lowered threshold. One difference between the conditions for horizontal and vertical determinations which might cause such a reduction is the starting position of the excursion. Possibly, being closer to an edge of the display screen, the starting point of the vertical excursion may have had a more effective frame of reference.

The last condition to be investigated involved the placement of the target at 90°, which meant a smaller visual angle subtended by a given distance of movement. The decrease in visual angle subtended by a given distance would lead one to expect a higher threshold of motion in terms of distance moved in the display, i.e., inches per second. This is seen to be the case. Moreover, a movement distance of 1 inch at 90°, which subtends a visual angle of 50', which may be compared with the (approximately) 40' subtended by 1/4 inch at 0°. The thresholds for these two conditions are quite close, in terms of visual angle. This is somewhat surprising since luminance and resolution thresholds are higher at 90° than at 0°. Evidently azimuth has little or no direct effect on the threshold of motion; thresholds are different at the 90° position only to the extent attributable to the change in visual angle.

7.0 Experiment V. Perception of Rate of Motion in a Three-Dimensional Display

An important consideration for many potential applications of a volumetric display is the operator's ability to discriminate the relative rates of motion of targets in the display volume. In particular, the effect of target position on this discrimination needs to be assessed. An indication of any consistent bias is desired as well as a measure of sensitivity. Therefore, a procedure was used in this experiment which required the subject to match (adjust) the rate of motion of one target with that of another target differing in initial position and direction of motion. To provide an indication of the extent to which the results are a function of the experimental method, some experimental conditions were replicated using the method of constant stimuli instead of the method of adjustment.

The selection of conditions and parametric values for this experiment was based on consideration of possible applications. For example, to be of value in most practical applications, a judgment of motion rate must be based on target motions of short extent relative to the dimensions of the display. Thus, a fixed extent of motion of 0.5 inch was used, although available data indicate that a greater extent would result in lower thresholds. Also, since the speeds studied should be suitable for scaling real-world motion into the display, the range of target speeds (in terms of minutes of visual angle/second) was lower than the region in which best rate discrimination has been reported in previous studies by Hick (1950) and Notterman and Page (1957). In short, the purpose of the experiment was to determine the differential threshold motion under conditions believed to have practical utility rather than to determine the conditions yielding a minimal rate threshold.

7.1 Procedure

For the experimentation with the method of adjustment, the standard target (St) and comparison target (Co) were presented alternately on each trial with St always first. The end of the St target sweep triggered the start of Co sweep, so that this cycling of St and Co continued until the subject completed his adjustment of Co target speed. To investigate horizontal target motion, the St target was always located at 0° azimuth; the Co target at one of eight azimuth positions: 0°, 45°, 80°, 135°, 180°, 225°, 260°, 315°. (When presented at 0° azimuth, the position of the Co target was slightly displaced vertically relative to St.) Both St and Co targets moved outward radially and horizontally on each sweep for a constant distance of 0.5 inches, starting at a point 1.5 inches from the center of rotation and at mid-altitude. Four St target speeds were used: 0.07, 0.14, 0.27 and 0.68 inches per second.

Vertical target motion was also investigated at the same four St target speeds. The procedure was identical except that both targets moved upward 0.5 inches from the bottom of the display screen. St was always presented at 0° at a distance of 1.5 inches from the center of the display. Two azimuth positions of Co were studied: 0° at a slightly larger radius than St, and 180°, at the same radius.

The subject viewed the display from the standard viewing position so that the St target, at 0°, moved in the plane normal to his line-of-sight. The subject varied the speed of the Co target by means of a rotary knob controlling a potentiometer. The range over which the subject could vary Co speed was appropriately adjusted prior to each trial so as to include speeds both faster and slower than the St, and at which the difference in rate was readily perceptible.

A session consisted of 40 trials at one location of the Co target with each of the four St target speeds being presented on ten trials in accordance with a predetermined random sequence. Before each trial, the subject set his control at one or the other extreme to provide alternate ascending and descending trials. The cycling of St and Co targets on each trial continued until the subject signalled the experimenter that he had completed the rate-matching adjustment. The experimenter then recorded the sweep time set by the subject and adjusted St speed and the range of adjustment of Co speed for the next trial.

Each subject served in 10 such sessions of 40 trials, one for each of the eight conditions with horizontal target motion and the two conditions with vertical motion. A different random order of conditions was used for each subject. The subject was given a short rest period (remaining in the display room) after the first 20 trials of each session. Session length was approximately 40 minutes.

In addition to the data collected by the adjustment method described above, differential thresholds were determined by a forced choice method of constant stimuli. The same four St target speeds were used. Both St and Co targets travelled outward horizontally for a distance of 0.5 inches at 0° azimuth. On each trial, the Co target was presented immediately after the St target. After this single presentation of St and Co, the subject was required to make a judgment of "faster" or "slower", even if the rates of the two targets appeared equal. At each St speed, ten bracketing speeds of the Co target were presented in a random sequence in which each Co speed occurred ten times. A different random order of the four St speeds was used for each subject.

7.2 Results and Discussion

The results are analyzed and presented in terms of target traverse (or sweep) time rather than target rate. This form of analysis is partly a matter of experimental convenience, since the data recording was in terms of sweep time in seconds. However, a more significant reason is that it seems to have been generally used in motion discrimination experiments. Most relevant reports are not explicit on this point, but it appears that Weber ratios and similar measures are usually computed in terms of time, although discussed in terms of rate discrimination. In order to provide comparability of data, the analysis follows this apparent convention even though the underlying logic seems open to question. (It would be convenient if distribution parameters computed in terms of time could be convenient if distribution parameters computed in terms of time could be converted to the corresponding parameters in terms of rate.. For any assumed form of distribution of time scores, it is possible to develop equations and nomographs for deriving the corresponding rate parameters. That is, having specified the mean and standard deviation of the time distribution, the mean and standard deviation of the corresponding rate distribution can be determined. This conversion has been examined under the assumption of normality for the distribution of time scores and found to be strongly dependent on the ratio of mean to standard deviation. If the mean of the time measures is large with respect to the standard deviation, the distribution of time measures is confined to a region over which a linear relationship of time and rate holds to a good approximation. Our analysis indicates that the present data, and probably rate discrimination data in general, are not well suited to this conversion.)

For the method of adjustment data, the following measures were determined for each subject under each experimental condition: mean, constant error, standard deviation, and root mean square error with respect to the standard target value.

The data analysis in terms of constant error is shown in Figures 7-1, 7-2 and 7-3. Figures 7-1 and 7-2 show the effect of azimuth position of the Co target on the mean adjustment of Co traverse time. Figure 7-1 shows the data for the four St speeds separately; Figure 7-2 presents average data for all four St speeds. In these figures, percent constant error in traverse time is represented by the distance of the plotted data points from the horizontal reference line. A Friedman two-way analysis of variance indicates that the variation in constant error with Co azimuth position is significant at the 0.05 level for subject MK and nearly so for subject ML. It can be seen by comparison of the four plots of Figure 7-1, that each subject shows some consistency in the pattern of his over and under-estimates. The patterns for the two subjects differ considerably, however, and neither pattern suggests any simple explanation.

A reference line has been included in the plots of Figures 7-1 and 7-2 to indicate the Co traverse time required to maintain a constant rate of motion in terms of visual angle as the Co azimuth position changes. It can be shown that azimuth angle has a marked effect on the visual angle subtended by a constant radial distance in the horizontal plane of the display, as viewed from the standard viewing position. In the context of the present experiment, this effect would result in large variation of Co traverse time settings as a function of Co azimuth, if the subject adjusted Co to maintain a constant angular rate of motion with respect to his eye position. The maximum deviation is at 90° where, as shown by the reference lines, traverse time must be reduced to little more than half its 0° value in order to maintain constancy of angular motion. Perhaps the most striking and practically significant aspect of the constant error data is the absence of the deviations associated with constant angular motion. The obtained deviations are much smaller in magnitude and even fail to show a consistent trend relative to constant rate reference line. Such a result may be interpreted as evidence for the operation of some sort of perceptual constancy or compensation. However, a simpler explanation would appear to be

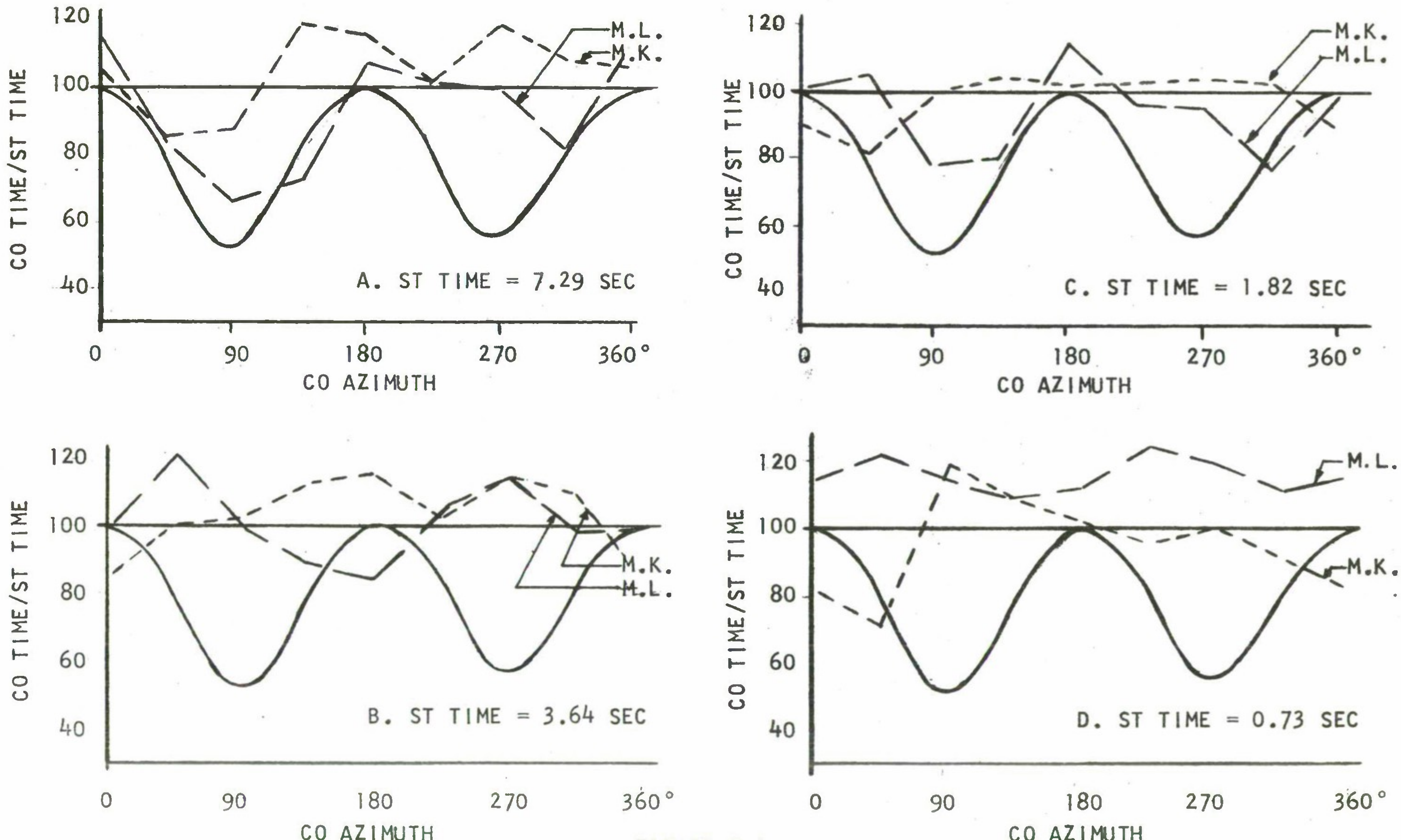


FIGURE 7-1

MEAN TRAVERSE TIME OF COMPARISON TARGET AS A PERCENTAGE OF STANDARD TARGET TRAVERSE TIME. PLOT FOR EACH ST TIME SHOWS EACH SUBJECT'S MEAN CO ADJUSTMENT AS A FUNCTION OF CO AZIMUTH POSITION. HORIZONTAL REFERENCE LINE INDICATES CO SETTING FOR EQUAL TRAVERSE TIME. PEAKED LINE INDICATES CO SETTING FOR CONSTANT RATE IN TERMS OF VISUAL ANGLE

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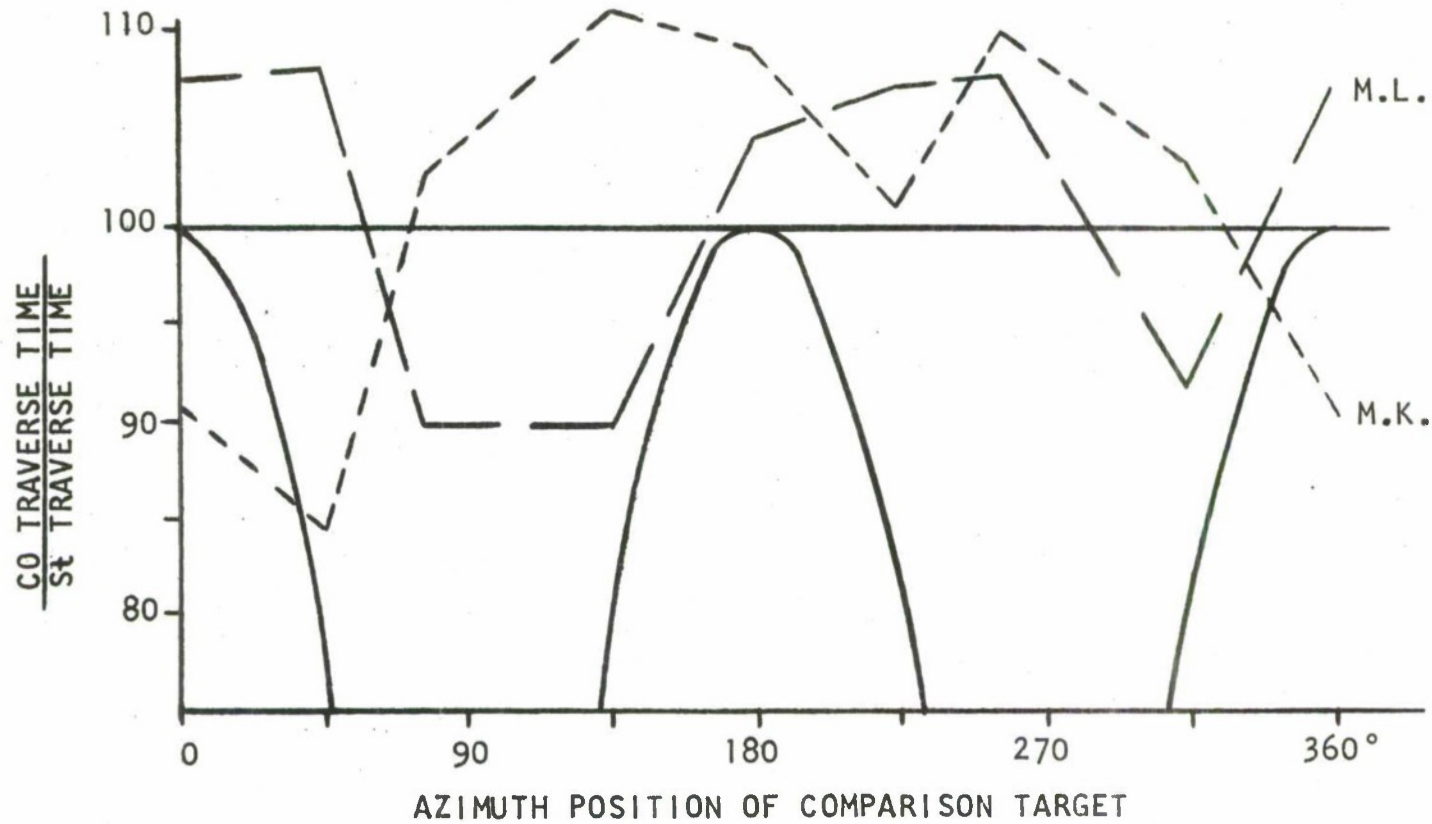

FIGURE 7-2

MEAN TRAVERSE TIME OF COMPARISON TARGET AS A PERCENTAGE OF STANDARD TRAVERSE TIME AVERAGED OVER FOUR St SPEEDS (SEE FIGURE 7-1)

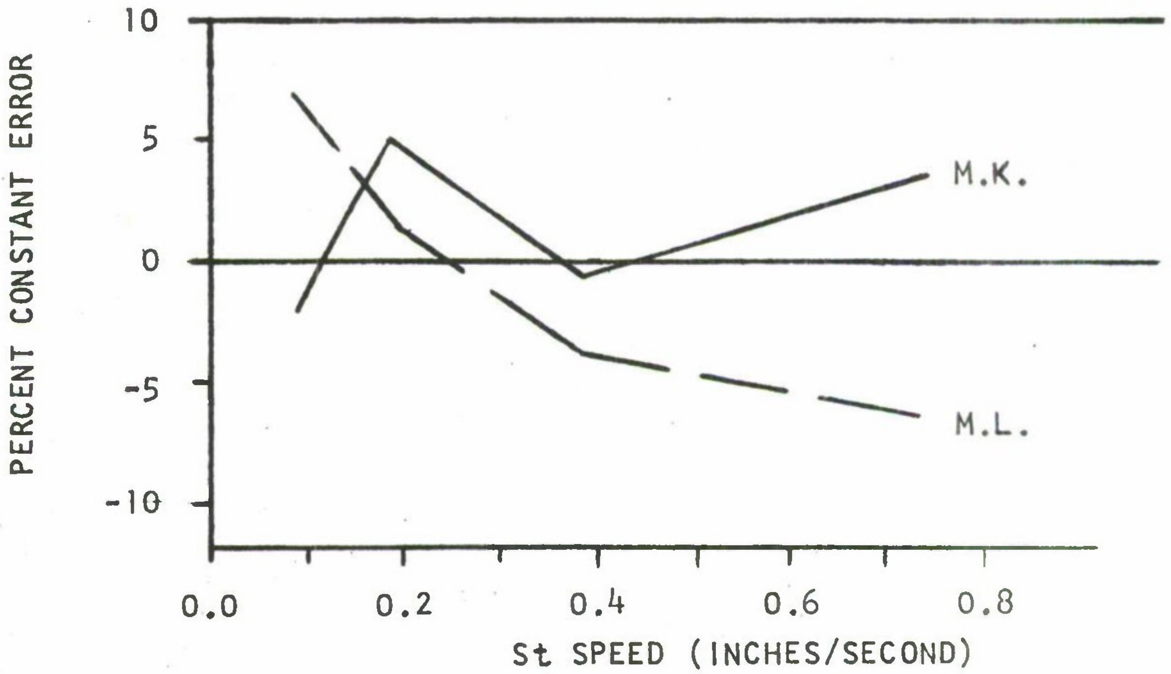

FIGURE 7-3

PERCENT CONSTANT ERROR IN TRAVERSE TIME AS A FUNCTION OF St TARGET SPEED

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that the subjects were judging time rather than rate, i.e., that Co traverse time was adjusted to match that of the St target without regard for visual rate of motion. The present experiment offers no basis for discriminating among these alternative explanations however, and a rather elaborate experimental design would be required for this purpose.

It may be said, though, that the introduction of the third dimension by means of azimuth variation of the Co target did not result in any consistent biasing effect. Although the obtained constant errors are large enough to warrant further analysis directed toward their reduction or elimination, there is no evidence that they are related to the three-dimensional nature of the display.

Another aspect of the constant error data is shown in Figure 7-3 which shows percent constant error as a function of the speed of the St target. The constant errors shown here are algebraic averages over all azimuth positions of the Co target. This averaging is open to some question in view of the previously reported significant effect of azimuth position on constant error. However, it is of interest to see whether a consistent pattern will emerge. For one subject, an orderly function was obtained, for the other subject, there appears no consistent effect of St target speed. However, a Friedman two-way analysis of variance indicates a significant effect of St rate on constant error for each subject. For subject ML, constant error goes steadily from positive to negative as the speed of the St target decreases. This subject tends to set the Co target at a slower rate than St when St is fast, and at a faster rate than the St when St moves slowly, i.e., this subject's settings tend to regress toward the mean St rate, a not uncommon occurrence in psychophysical studies. For subject MK, it can only be said that no consistent pattern is evident. Once again, there appear to be differences between the subjects in their constant error performance. Since constant error does not appear to be strongly controlled by factors external to the subject, this may indicate the possibility of reduction of constant error with practice.

Absolute constant error, taken without regard to sign, is also of interest. Unlike the algebraic constant error, the absolute CE was not found to vary significantly with St target speed. However, a trend is apparent in the data for each subject which is quite similar to the trend of the variable error data.

The error data are analyzed in terms of two component errors. The standard deviation around the mean of the Co settings is taken as a measure of variable error. The absolute constant error is taken as a measure of consistent bias in the Co settings with respect to the rate of motion (or, actually, the traverse time) of the St target. These two error measures combine to yield a composite or total error measure, the root mean square (rms) error with respect to St speed. Since rms error is equal to the square root of the sum of the square of the constant error plus the square of the standard deviation, any trend in rms error is necessarily indicative of a comparable trend in one or the other, or both, component errors. In the present data, the Friedman two-way analysis of variance indicates significant variation in rms error with St speed for each subject. Although the same test fails to reach significance for constant error (absolute) and standard deviation, the appearance of trends in these component error measures becomes meaningful when considered in conjunction with the rms error. In general, the same trend is apparent for all three error measures for each subject. This is shown graphically in Figures 7-4, 7-5 and 7-6.

Figures 7-4 through 7-6 show percent error in traverse time as a function of St target speed for horizontal motion. Figures 7-4 and 7-5 present the data for the two subjects separately. Figure 7-6 is the comparable plot for both subjects combined. The ordinate in these plots is mean percent error with respect to the St target speed. Thus, the error measures are in a form suitable for comparison across the four St speeds. All three measures suggest that there is an optimum St speed within the range of target speeds studied. That is, as rate of target speed increases, the various percent error measures first decrease and then increase again. (The comparable data for vertical motion shown in Figure 7-7 does not show a significant trend.)

The likelihood of an optimum is strengthened by the findings of previous investigators. Notterman and Page (1957) noted an apparent optimum in some earlier rate discrimination data (Hick, 1950). Replicating the earlier experiment, they confirmed the presence of the optimum. At least one subsequent study (Mandriota, 1962) has produced several sets of data showing similar trends. However, the optimum in the present data appears to lie at St speeds lower than the optimum region previously reported. Notterman and Page interpret their data and Hick's data as indicating a minimum in the 1-to-3 degrees/second region. Mandriota's data is roughly comparable with respect to the

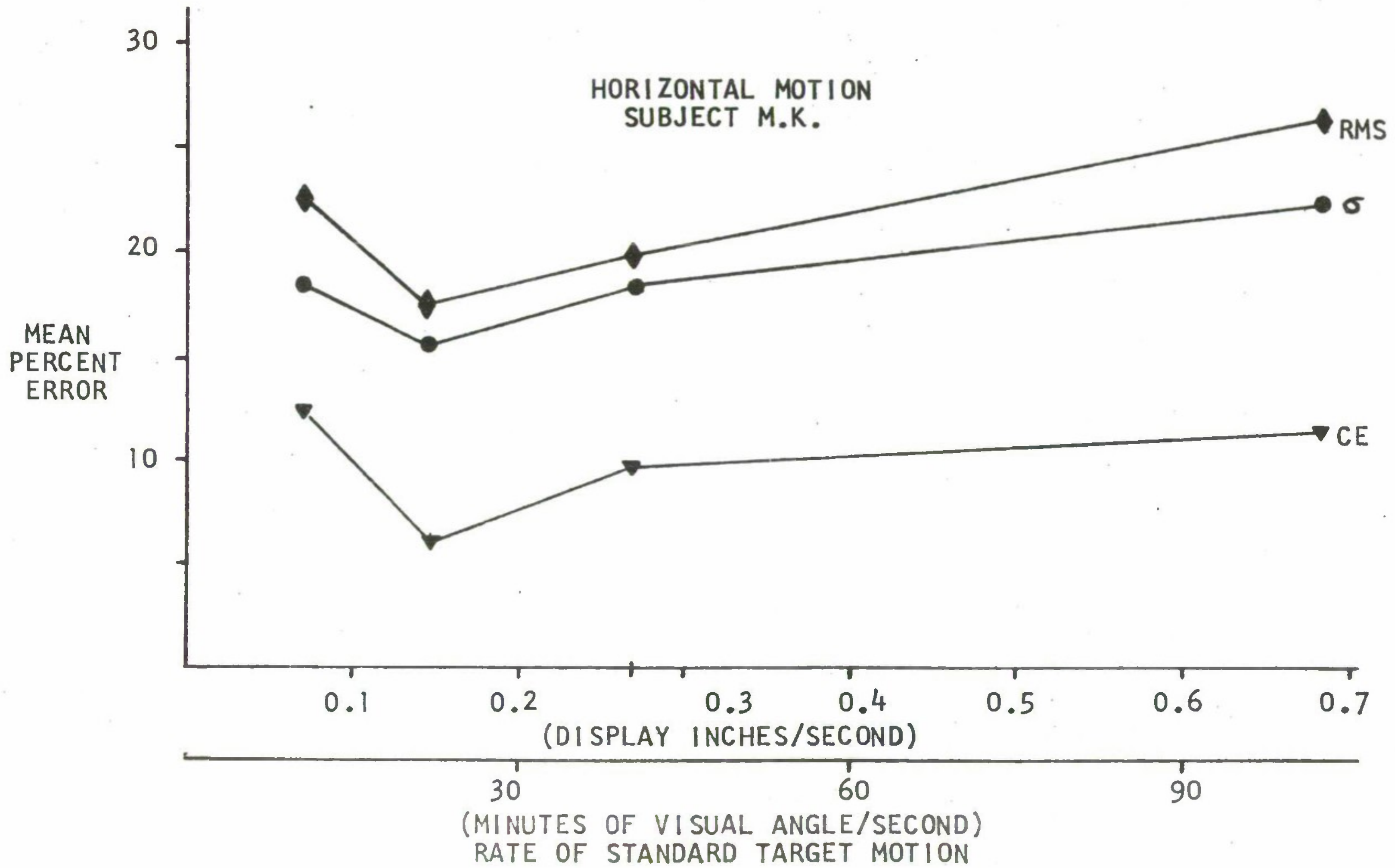

FIGURE 7-4

PERCENT ERROR IN TRAVERSE TIME FOR SUBJECT M.K. AS A FUNCTION OF TARGET SPEED FOR CONSTANT ERROR, STANDARD DEVIATION AND RMS ERROR

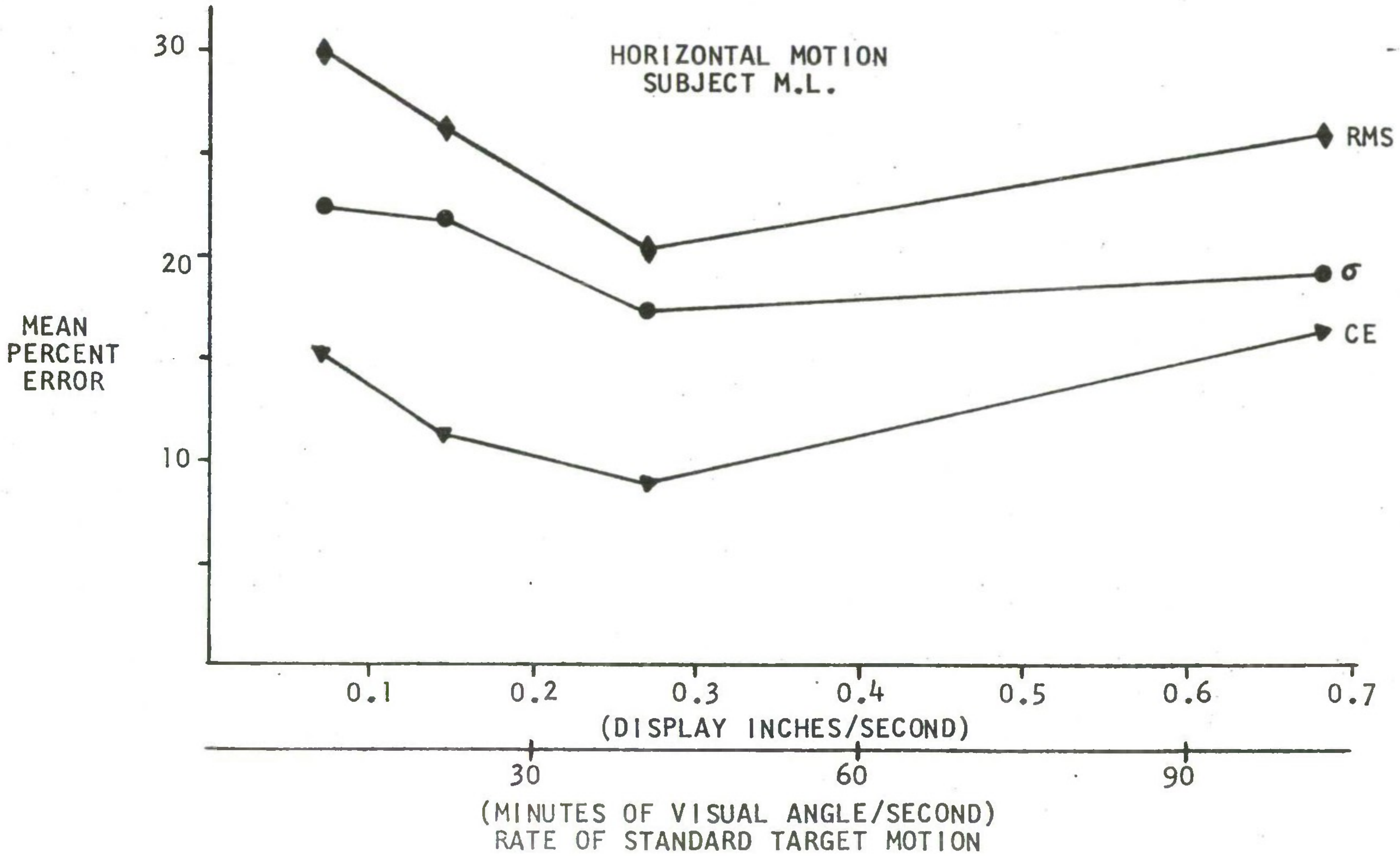

FIGURE 7-5

PERCENT ERROR IN TRAVERSE TIME FOR SUBJECT M.L. AS A FUNCTION OF TARGET SPEED FOR CONSTANT ERROR, STANDARD DEVIATION AND RMS ERROR

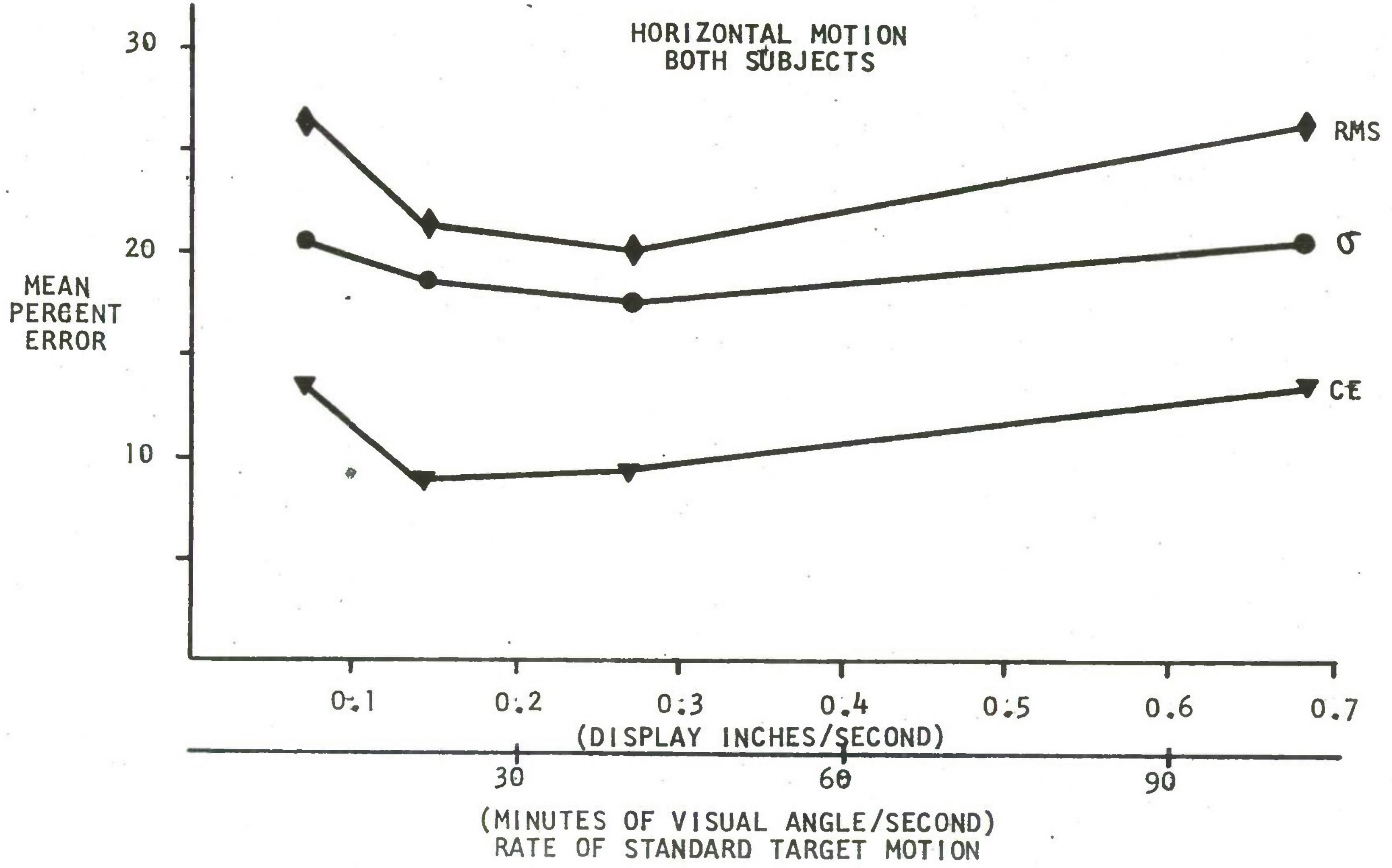

FIGURE 7-6

PERCENT ERROR IN TRAVERSE TIME FOR BOTH SUBJECTS AS A FUNCTION OF TARGET SPEED FOR CONSTANT ERROR, STANDARD DEVIATION AND RMS ERROR

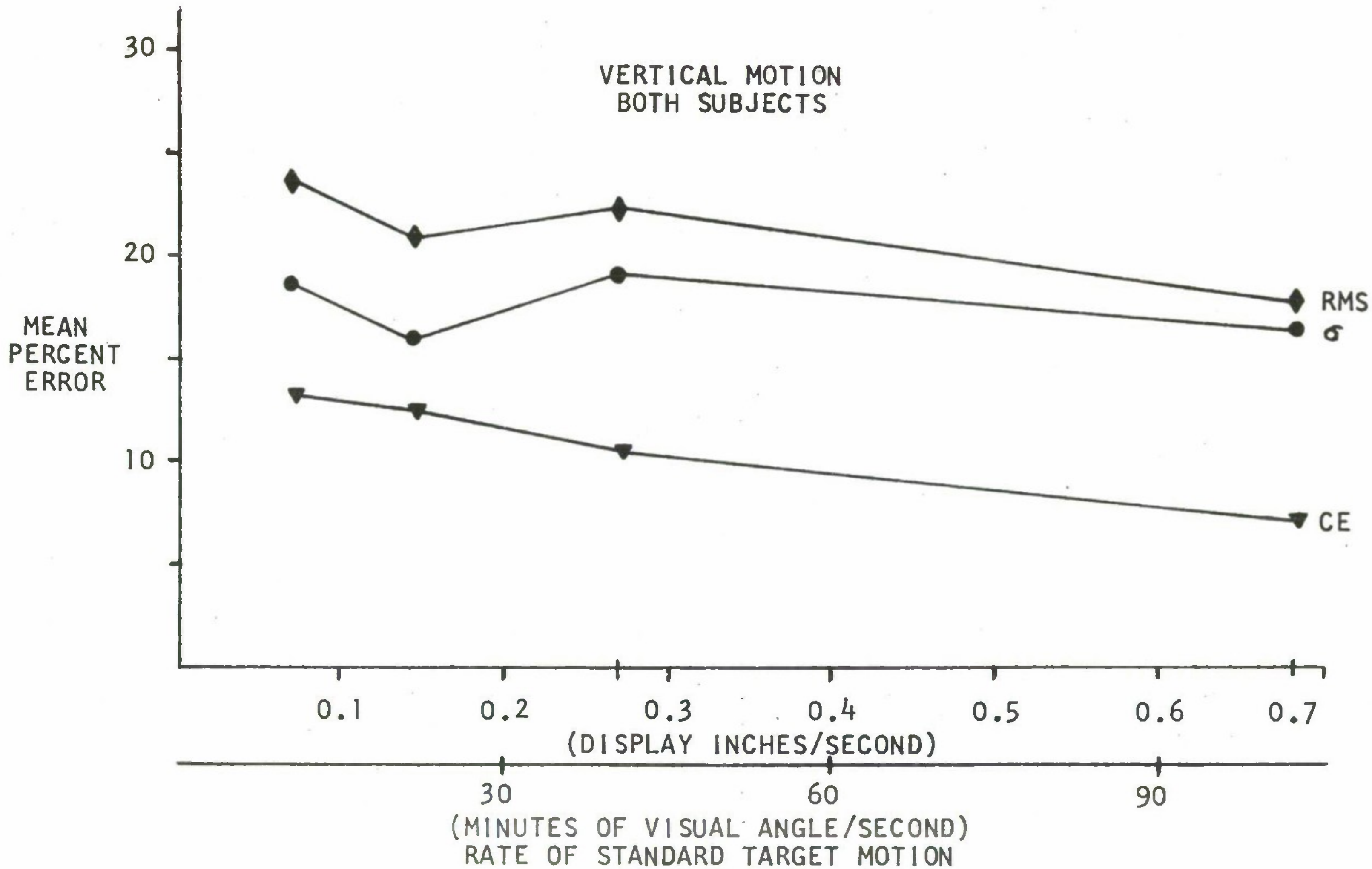

FIGURE 7-7

PERCENT ERROR IN TRAVERSE TIME FOR BOTH SUBJECTS AS A FUNCTION OF TARGET SPEED FOR CONSTANT ERROR, STANDARD DEVIATION AND RMS ERROR VERTICAL TARGET MOTION lower limit of the optimum region, but indicates a much wider optimum range, i.e., the differential threshold increases less rapidly with increasing St rates than in previous data. In the present data, the optimum St rate would appear to lie in the vicinity of 20-40 minutes of visual angle per second. Actually, the optimum (if indeed there is one) is not very pronounced, and discrimination performance does not vary greatly over the range of St speeds studied.

A plausible explanation is available to account for the lower St rate range of the apparent optimum. The extent of target traverse used here is much shorter than in the above referenced studies. Under the conditions of the present study, the 0.5 inch linear extent of motion at 0° azimuth was equivalent to an angular motion of 75 minutes of visual angle. In previous studies, the comparable value has been of the order of 4 to 6 degrees of visual angle. Clearly, performance in the present experiment was limited at the upper end of the St rate range by the very short duration of target presentation, the fastest target completing its 0.5 inch traverse in only 0.73 seconds. Had a longer target excursion been used, it is likely, in view of previous findings, that optimum discrimination would have occurred at higher values of St target rate. It is also quite possible that performance level at the optimum would be better (i.e., the differential threshold would be lower) than that obtained in the present experiment. Experiments with a greater extent of target motion generally show a continued improvement in performance through and beyond the St rate range of this experiment.

It must be remembered, however, that the short fixed extent of target motion was purposely selected in consideration of probable applications of the display. It was presumed that the rate discriminations of practical interest for most applications would be those which could be achieved over a small extent of motion relative to the display dimensions. In this context, the relevant consideration is the quality of the discrimination actually obtained. The percentage error scores appear quite large and, of course, it would be desirable if they could be substantially reduced. In view of the possibility that percent error might vary greatly with experimental method, a limited replication was made using the method of constant stimuli. The results are shown in Table 7-1 and Figure 7-8. Figure 7-8 shows the traditional Weber ratio as a function of St target speed. For purpose of comparison, the comparable data obtained with the method of adjustment is

TABLE 7.1

Mean, SD, Δt, % SD, Weber Ratio ($\Delta t/t$) and CE at four standard target speeds

SUBJECT	Time	7.29 sec.	3.64 sec.	1.82 sec.	0.73 sec.
	Rate	0.07 ips	0.14 ips	0.27 ips	0.60 ips
	Measure				
	Mean	6.59	3.46	1.87	.71
	SD	1.10	.38	.43	.082
M.L.	Δt (.67 SD)	.74	.31	.29	.055
	% SD	15.09	10.44	23.62	11.23
	$\Delta t/t$	.10	.070	.16	.075
	CE	-.70	-.18	.05	-.02
	Mean	7.22	3.72	1.75	.64
	SD	.91	.42	.29	.066
M.K.	Δt (.67 SD)	.61	.28	.19	.044
	% SD	12.48	11.54	16.57	9.04
	$\Delta t/t$	.084	.077	.11	.060
	CE	-.07	.08	-.07	-.09

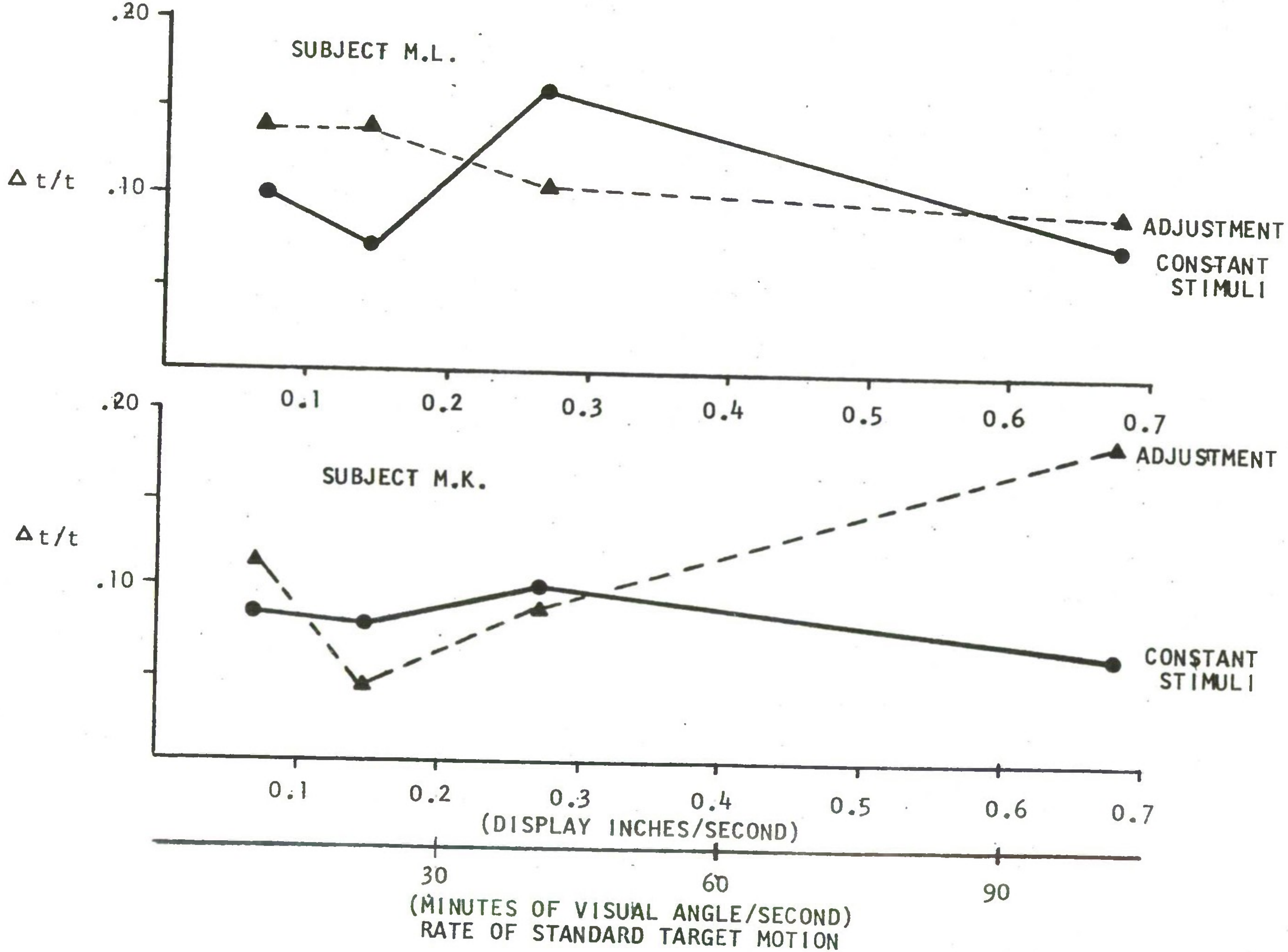

FIGURE 7-8
COMPARISON OF METHOD OF CONSTANT STIMULI AND METHOD OF ADJUSTMENT IN TERMS OF WEBER RATIO AS A FUNCTION OF TARGET SPEED

also shown. In general, data obtained with the two methods are quite comparable. While the method of adjustment will probably yield somewhat higher thresholds than some other psychophysical methods, the comparison shown in Figure 7-8 suggests that no great improvement due to method can be expected. However, examination of the data in terms of Weber ratio, as in Figure 7-8, gives a somewhat different impression of the level of error. Discrimination data of this sort is usually presented in terms of the Weber ratio, which yields a numerically lower value than the percent error figures generally used here. The conversion from percent error to Weber ratio for the adjustment data in Figure 7-8 is accomplished by multiplying the standard deviation by 0.67. Of course, manipulation of numbers does nothing to improve performance, but it does place the present data on a more appropriate basis for comparison with previously reported data. On this basis, the data obtained with the three-dimensional display compare favorably with data obtained with two-dimensional CRT displays.

8.0 Summary and Conclusions

A series of experiments was performed to evaluate some of the operating characteristics and provide a basis for the rules of application of a three-dimensional display device based on a CRT image projected on a rotating translucent screen. The factors investigated were: perception of the relative location of point targets in close proximity, perception of the location of point targets relative to the display boundaries, and the perception of moving targets. The principal results of the series were:

1. A subject's error in superposition of one "point" target on another is increased markedly when the targets are located along his line-of-sight. Superposition error at these locations is attributable mainly to constant error. These results hold for superposition in both range and altitude. However, the line-of-sight error can be greatly reduced by moving targets slightly to the right or left or, conversely, moving the head so as to change the line-of-sight.

2. The resolution of the display, defined as the smallest inter-target distance necessary for the detection of a second target, was found to be approximately .05 inches, or 2 degrees of arc. These values were also markedly affected by azimuth position, but this could be greatly reduced as above.

3. Estimation of the location of point targets was found to be quite accurate, involving overall mean errors of only 0.5 to 1.5 inches and individual axis direction errors of 0.0 to .5 inches. Errors in estimation are correlated with true target location but, in general, the relationships vary significantly between subjects. In addition, the type of errors made tended to maintain the integrity of the line-of-sight. That is, errors in altitude tend to complement fore-aft errors, and lateral errors tend to be minimal so that the perceived location of the target, although displaced from the true location, tends to remain on the line-of-sight. Constant error of judgment was found to represent a sizeable portion of the total error with regard to the fore-aft axis, but this was not generally true for the altitude and lateral axes.

4. The threshold of motion was found to increase as extent of movement decreased. Increasing ambient illumination decreased threshold of motion by making visible portions of the display which might serve as a reference. Azimuth position affected threshold markedly when the former was measured in inches per second, but only slightly when it was measured in degrees of visual angle per second.

5. A subject's estimate of rate of target motion, as judged by comparison with a second moving target, varied with rate of motion itself, being most accurate in the middle ranges of target speed. The constant component of the total error varied with the relative position of the two targets in azimuth, although this parameter seemed to have little consistent effect on variable error. The method of rate estimation, i.e., active control (method of adjustment) or passive judgment, (method of constant stimuli) had little effect on the subject's rate estimate.

In general, it may be said that these experiments demonstrate the potential utility of a three-dimensional volumetric display device in operational systems requiring the rapid and accurate monitoring of both stationary and moving targets. Considering the "worst case" conditions utilized primarily in the experiments, it can be concluded that estimation of target location and movement was found to be highly accurate and relatively rapid. There is no question, however, that a good deal of continued research is necessary, especially under conditions of multiple target presence and visual noise.

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13. ABSTRACT

A series of experiments was performed to evaluate some of the operating characteristics and potential utility of a volumetric (i.e., real) three-dimensional display produced by projection of a CRT image onto a rotating translucent screen. Some of the variables tested were perceptibility of relative location of point targets in close proximity, perception of location of point targets relative to display boundaries and perception of absolute and relative motion of targets in the volume. Estimation of location and motion were found to be highly accurate and quite rapid. While the results do not point conclusively to specific applications, the utility of volumetric 3-D in making fine position and motion discriminations has been demonstrated. Further study would be required to ascertain utility in practical situations such as air traffic control, space suveillance, etc.

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